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MATERIALS FOR POTASSIUM LUBRICATED JOURNAL BEARINGS

Quarterly Progress Report No. 1
For Quarter Ending July 22, 1963

EDITED BY R. G. FRANK

prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CONTRACT NAS 3-2534

SPACE POWER AND PROPULSION SECTION
MISSILE AND SPACE DIVISION
GENERAL ELECTRIC
CINCINNATI 15, OHIO

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MATERIALS FOR POTASSIUM LUBRICATED JOURNAL BEARINGS

QUARTERLY PROGRESS REPORT 1
Covering the Period
April 22, 1963 to July 22, 1963

edited by
R. G. Frank
Program Manager

approved by
J. W. Semmel, Jr.
Manager, Materials and Processes

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NAS 3-2534

Technical Management
NASA - Lewis Research Center
Mr. R. L. Davies

SPACE POWER AND PROPULSION SECTION
MISSILE AND SPACE DIVISION
GENERAL ELECTRIC COMPANY
CINCINNATI 15, OHIO

FOREWORD

The work described herein is being performed by the General Electric Company under the sponsorship of the National Aeronautics and Space Administration under Contract NAS 3-2534. Its purpose, as outlined in the contract, is to evaluate materials suitable for potassium lubricated journal bearing and shaft combinations for use in space system turbogenerators and, ultimately, to recommend those materials most appropriate for such employment.

R. G. Frank, Manager, Physical Metallurgy, Materials and Processes, is administering the program for the General Electric Company. L. B. Engel, Jr., D. N. Miketta, T. F. Lyon, W. H. Hendrixson and E. M. Bamberger are directing the program investigations. The design for the friction and wear tester is being executed by H. H. Ernst.

R. L. Davies of the National Aeronautics and Space Administration is the technical manager for this study.

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I. INTRODUCTION

This report covers the initial phase of a program, extending from April 22, 1963 to July 22, 1963, to evaluate materials suitable for potassium lubricated journal bearing and shaft applications in turboelectric space power generating systems operating over a 400°F to 1600°F temperature range. The critical role of bearings in such systems demands the maximum reliability attainable within today's state-of-the-art. Achieving this reliability requires an interdisciplinary approach utilizing the best mechanical designs of journal bearings combined with the selection of the optimum materials to serve as the structural members. Satisfying this latter requirement constitutes the aim of this program.

A number of investigators have conducted studies in this field and their contributions have advanced the state-of-the-art considerably.* Although their work is significant, there are no common criteria for a comparison of the existing data. Therefore, establishing a unified approach to the development and evaluation of materials for potassium lubricated bearing application is deemed essential. The program involves a comprehensive investigation of material properties adjudged requisite to reliable journal bearing operation in the proposed environment. This includes: 1) corrosion testing of individual materials and potential bearing couples in potassium liquid and vapor, 2) determination of hot hardness, hot compressive strength, modulus of elasticity, thermal expansion and dimensional stability characteristics, 3) wetting tests by potassium, and 4) friction and wear measurements of selected bearing couples in high vacuum and in liquid potassium.

In cooperation with the cognizant NASA technical manager, candidate materials will be selected from a compilation of existing data on avialable materials. The materials reviewed fall into four board categories:

- Superalloys and refractory alloys with and without surface treatment.
- Commercial metal bonded carbides.
- Refractory compounds such as stable oxides, carbides, borides and nitrides.

*See Section VIII. Bibliography

- Cermets based on the refractory metals and stable carbides.

Each material will be procured from appropriate suppliers to mutually acceptable specifications and subsequently subjected to chemical, physical and metallurgical analyses to document its characteristics before utilization in the program. After the documentation of processes and properties, the candidate materials will undergo corrosion, dimensional stability, thermal expansion, compression and hot hardness testing. Considering the bearing material requirements and the preliminary information obtained on materials subjected to both potassium and non-potassium testing, a number of materials combinations will be selected in cooperation with and subject to the approval of the NASA technical manager. Potassium corrosion and wetting tests and friction and wear measurements in high vacuum and liquid potassium will then proceed with these materials combinations.

The ultimate product of this program will be a recommendation, substantiated with complete documentation, of those materials which have the greatest potential for use in alkali metal journal bearings in high speed, high temperature, rotating machinery for space applications. Hopefully, the results will indicate the future course of alloy or material development specifically designed for alkali metal lubricated journal bearing and shaft combinations. Recommendations will also be made on the application of this program to the development of journal bearings and shafts that will operate reliably over extensive periods of time.

II. SUMMARY

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An initial compilation of chemical, mechanical and physical properties of selected materials, representing seven major classes of materials, was completed from data obtained from the literature and from materials producers. From this review, 35 materials were recommended to be considered for inclusion in the test program. Although the candidate materials were compared against a list of properties and characteristics that were considered important with respect to journal bearing operation, the selection of the specific materials was made primarily on the basis of either chemistry, producibility or some specific property that is inherent in a particular material.

Preliminary test plans for the corrosion, hot hardness, compression, thermal expansion, dimensional stability and friction and wear investigations and for the purification and analyses of potassium were prepared for submission to NASA for review and approval. Plans for wetting tests and friction and wear measurements with liquid potassium are in preparation and will be submitted at a later date.

Of the three vacuum test facilities being purchased for the program by General Electric, two have been received and installed; drawings of the third unit have been sent to vendors for quotations. One of the vacuum systems, to be used for the corrosion investigation, consists of a bakeable 24-inch diameter x 54-inch high chamber with a 1000 ℓ/sec getter-ion pumping system which has been checked out in the 10^{-10} torr range. The second vacuum system, to be used for the friction and wear investigation, consists of a bakeable 18-inch diameter x 30-inch high chamber, also with a 1000 ℓ/sec getter-ion pumping system. Checkout tests on this vacuum system are in progress. The third system, to be used for the compression tests, will consist of a specially designed vacuum chamber and load train with a mechanical strain measuring system.

Considerable effort was devoted to the design of the vacuum friction and wear test apparatus to meet the required test conditions: maximum temperature, 1600°F; vacuum, 1×10^{-9} torr; surface speed, 5000 sfm; load, to 0.2% yield strength (hertzian). The design, including assembly drawings, has been completed. Also, the design for the load train for the compression tests and the capsule and furnace arrangement for the corrosion investigation has been initiated.

Author

III. MATERIALS SELECTION

A search of the literature was initiated to augment existing information available to the program. A computer run utilizing the General Electric Automatic Information Retrieval System realized 140 abstracts covering the studies of friction and wear and hot hardness characteristics of bearing materials. The bibliography included is a listing of the most pertinent work uncovered.

A review of the work completed indicates that a number of investigators have demonstrated the good potential of the liquid alkali metals to provide boundary lubrication and hydrodynamic action in journal bearings.[74-85] However, because of the extremely low viscosity of the liquid alkali metals, i.e., 1 centipoise versus 10 to 1000 centipoise of lubricating oils, boundary lubrication will probably occur and some sliding contact between the bearing and journal must be expected. Consequently, the theories of Bowden and Tabor[87] on the sliding contact of solids and, later, the theories of Coffin[76] on the sliding contact of solids in sodium were considered in making the recommendations for the selection of materials for the program.

Two of the most important factors to consider in selecting materials for a potassium lubricated journal bearing are:

1) The tendency for the sliding materials to "alloy".

2) The effect of the potassium environment on the surface chemistry of the bearing materials.

The first factor is based on the molecular theory of friction where adhesion (or cohesion) can produce local welding of the mating asperities of the sliding materials. The amount of bulk or interfacial tearing that occurs, then, determines the frictional energy. Since interfacial tearing generally results in less wear than base metal tearing, mating materials with high cohesive strengths and low adhesive strengths should be selected for best performance. One method that has been used to predict the adhesive strength of two materials is to determine the degree of wetting of one material against the other, where a zero contact angle represents good adhesion and a 180° contact angle represents poor adhesion.

(74-85) Numbers refer to references in Bibliography, Section VIII.

To minimize the adhesion between two mating materials, ideally the materials should have a low solubility in one another and no tendency to form compounds. If a compound is formed, it, too, should have a low solubility in the substrate and, in addition, a low strength level in comparison to that of the base materials. In other words, increased surface damage would be expected as the tendency to alloy, i.e., increased solubility and formation of strong compounds, increases. Because of the importance of this factor, obviously a list of individual materials cannot be selected without considering the possible journal bearing combinations.

The second factor, i.e., potassium environment, is important from the standpoint of corrosion and how the corrosion reaction and/or products will affect the surface chemistry, surface condition and the adhesion or strength of the bond between the mating surfaces. Corrosion reactions can influence the surface finish by the formation or removal of protective films and by intergranular attack or selective attack along certain crystallographic planes. The strength of the materials at the surface can be affected detrimentally by selective leaching of alloying elements. A major benefit derived from the presence of the potassium will be its cooling effect in reducing the interfacial temperature between the sliding surfaces. This is important when considering hardness and strength of the surface layers as well as the existence of a transition temperature from shear action to welding of the asperities. The latter is of concern especially if lower melting point materials are considered. The influence of possible corrosion interaction between bearing combinations in the presence of a columbium alloy must also be considered in the selection of the materials for evaluation in this program.

In addition to the two major consideration cited, several other factors enumerated below will affect the bearing performance and the rate at which surface damage will occur.

1) Dimensional Stability: To maintain proper clearances, dimensional changes caused by metallurgical instability must be negligible. Also, thermal expansion characteristics between the bearing and journal assembly must be considered for their effect on clearance and wear-in.[76]

2) Hardness: Generally, a high hardness at the operating temperature is considered desirable for superior bearing performance. Not only is a higher load-carrying capacity indicated by a higher hardness but also a higher surface finish is usually possible with the harder material. The better surface finish results in more uniform surface areas in contact (fewer asperities) and, therefore, there is less tendency for wear. For bearing couples, it is generally

desirable to have one of the materials harder than the other to facilitate wear-in of the couple. If both materials are hard and brittle, the low fracture strength will cause fracture of the weaker asperities; the resultant debris can cause severe surface damage due to abrasion.[92]

3) Melting Point: The higher the melting point, the lower the atomic mobility of the materials in the interfacial layers will be, therefore, favoring lower diffusion rates and less tendency to bond. Soft, low melting point metals have been observed to transfer to the mating material due to the large shear force.

4) Compressive Strength/Elastic Modulus: A high compressive strength and elastic modulus at the operating temperature will permit high loads to be imposed without plastic deformation and with minimum elastic deformation of the bulk material.

5) Shear Strength: A low shear strength or, rather, a high compressive strength/shear strength ratio is preferred to promote interfacial shear. With brittle materials, where plastic deformation cannot occur, a high shear strength is desirable to prevent debris from causing damage due to abrasion.

6) Thermal Conductivity: A high thermal conductivity will favor a more rapid dissipation of heat caused by friction and thereby further minimizing the tendency for interfacial bonding by diffusion.

7) Wetting: Wetting of the surfaces of the bearing/journal by potassium will promote boundary lubrication and provide increased load-carrying capacity.

8) Surface Finish: The better the surface finish of the harder material of the bearing couple, the less tendency there will be for the transfer of the softer material to the harder material.

9) Other Mechanical Properties: In general, the materials to be considered for potassium lubricated journal bearing combinations should have sufficient impact strength to withstand shock loading. Also, high thermal and mechanical fatigue strengths are favored to prevent spalling and cracking of the surface under cyclic conditions of load and temperature.

10) Operating Conditions: Low operating temperatures, low velocities and light loads favor low diffusion rates of the mating materials across the interface.

Two meetings* were held at General Electric, Evendale, Ohio, to establish the criteria by which the candidate materials are to be selected. As a result of these meetings and from the considerations described above, a list of properties and characteristics to be used as a basis for the selection of the materials was prepared and submitted to NASA for review.

In an attempt to obtain as much recent data as possible, letters of inquiry were sent to twenty-three companies who have had experience in producing materials of interest to this program. The vendors were apprised of the materials classes to be investigated, the properties and characteristics to be used as a basis for selection and the type and number of specimens required for the test program. Also, the vendors were requested to furnish technical data that were available for each material they would want considered for the program and any processing information that could be released as nonproprietary. Personal visits were made to twelve representative vendors for a more thorough discussion of the program, materials requirements, processing details, producibility and properties. Through these visits, reviewing numerous materials and obtaining data on only those materials of respective interest was possible. Even so, data was obtained on approximately eighty materials from fourteen vendors.

The data obtained on many materials, particularly those of interest for application in advanced space power systems, i.e., refractory metal bonded cermets, were quite limited. In those cases, approximation or general level behavior from a knowledge of their chemistry or of similar materials were used. However, data were available for a number of properties at room temperature, which were common to most of the materials, so that a comparative compilation is possible. Although the data at elevated temperature were too exiguous to provide a basis for comparison for all the materials, where available, they can be used for comparisons within one class of materials. Searching the literature will be continued to compile additional data on specific materials. When the literature search is completed, a topical report covering the results will be issued. Because of the limited data in some areas, modifications to the initial list of properties and characteristics were necessary; Table I is the revised list of properties from which material comparisons were made.

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*May 27, 1963 with R. L. Davies and J. O. Joyce, NASA-Lewis Research Center and June 6, 1963 with Dr. L. Coffin, General Electric, Research Laboratory.

TABLE I: PROPERTIES/CHARACTERISTICS USED AS BASIS FOR COMPARISON OF CANDIDATE MATERIALS

1. Chemistry
2. Resistance to Corrosion by Potassium
   a. Solution
   b. Selective leaching
   c. Grain boundary attack
   d. Attack of select crystallographic planes
   e. Chemical reaction/compound formation with K
3. Stability in Cb Alloy/K System
4. Hardness
   a. Room temperature
   b. Elevated temperature
5. Compressive Strength
   a. Room temperature
   b. Elevated temperature
6. Tensile Strength
   a. Room temperature
   b. Elevated temperature
7. Transverse-Rupture Strength
   a. Room temperature
   b. Elevated temperature
8. Modulus of Elasticity
   a. Room temperature
   b. Elevated temperature
9. Thermal Conductivity
10. Wear
11. Density
12. Producibility or Lore
   a. Commercial status
   b. Reproducibility of properties
   c. Fabricable into complex shapes
   d. High surface finish capability
   e. Lack of porosity
13. Method of Consolidation

Materials were reviewed for consideration as candidates for inclusion in the program from the broad classes listed in Table II. The specific materials were selected from each broad class for one or more of the following reasons: typical of a class, special chemistry, established good strength/hardness or chemical stability in potassium, commercially produced with reproducible properties and good densities (lack of porosity) and consideration of a proper balance between the various classes of materials. The candidate materials together with the data that were obtained using Table I are listed in Tables III, IV and V.

In presenting the data on the various candidate materials, it was desirable to consider both moderate and high temperature ranges of bearing operation so that a broader spectrum of materials, i.e., pure metals to hard metal compounds and ceramics, could be considered. An arbitrary temperature of 1000^{o}F was chosen to distinguish moderate temperature from high temperatures. Arbitrary decisions were also made in two other areas. First, although thermodynamic data, Table VI, indicated a material was unstable in a columbium/potassium system, from kinetic considerations at the moderate temperature ($<$ 1000^{o}F), the material was rated as stable. Second, when data were not available from the vendor, the producibility of a material was rated in accordance with its method of consolidation: excellent for cast or wrought metals and alloys; very good for liquid phase sintered cermets; good for cold pressed/sintered or hot pressed compounds; and unknown for materials that have not received much attention from industry.

The problem of ranking the candidate materials, to implement the selection of materials for evaluation in the program, was given serious thought. Although a mathematical approach is desirable, the large number of materials, the relatively large number of properties to rank, and the fact that much data are missing and/or questionable impede such an approach. Further consideration of the problem and the overriding factors of (1) chemistry, as associated with alloying tendency of possible pairs, resistance to potassium corrosion and relative stability in a columbium/potassium system, (2) producibility and (3) the need for experimental freedom to select materials for specific properties precluded that approach. After a careful review of the data in Tables III, IV, and V, considering the previous discussions concerning factors affecting performance of alkali metal lubricated journal bearings, materials were selected and recommended to the NASA technical manager for inclusion in the first phase of the program. These materials are listed in Table VII. The basis for the specific selections is discussed on the following pages.

Although the identification of a metallic material that could serve both as a shaft material and as the bearing surface offers significant advantages in the fabrication of the rotor, the service conditions imposed by advanced space power systems may

TABLE II: CLASSES OF MATERIALS REVIEWED

A. Nonrefractory Metals and Alloys

B. Refractory Metals and Alloys

C. Fe-Ni-Co Bonded Carbides

D. Carbides

E. Oxides

F. Borides

G. Refractory Metal Bonded Cermets

H. Other Materials
- Nitrides
- Silicides
- Sulphides
- Beryllides

TABLE III: CHEMICAL COMPOSITION AND CHARACTERISTICS OF CANDIDATE MATERIALS

Materials Class	Material	Source	Composition W	Co	Ti	Cb	Ta	C	Ni	Mo	Cr	Other	Resistance to K Corrosion[16]	Estimated Stability in Cb-1Zr/K System[16] Mod. T.	Elev. T.
A. Nonrefractory Metals, Alloys	Vasco-Hypercut	Vanadium[37,39]	1.5	8	(+1.15V,.22Si,.22Mn)			1.07	--	9.5	3.75	Fe Bal.		Stable	Unstable
	Vantro-S	Vanadium[37,39]	5.5	5	-	-	-	1.27	--	4.5	8.0	V 4.0			
	Vascojet MA-2	Vanadium[37,39]			-	-	-	0.55 + 18% alloying elements				Fe Bal.			
	Vasco 1741	Vanadium[37,39]	(+ 4V, .25 Mn)		-	-	-	1.3		1	17.5	Fe Bal.			
	Vascomax 300 CVM	Vanadium[37]	--	9	.6	(+ .1 Al, .003 B, .02 Zr)			--	4.8	--	Fe Bal.			
	Rex 49	Crucible[40]	6.75	5	-	-	-	1.1	--	3.75	4.25	Fe Bal.			
	L-605	Union Carbide[14]	15	Bal.	(+ Si 1.0, Mn 1.5)			.05-.15	9-11	--	20	Fe 3	Good 1850°F K, Na		
	L-605 Cold Reduced 20% and Aged	Union Carbide[15]	15	Bal.	(+ Si 1.0, Mn 1.5)			.05-.15	9-11	--	20	Fe 3			
	Alloy 6B	Union Carbide[16-19]	4.5	Bal.	(+ 2 Si, 3 Fe, 2 Mn)			1.1	3	1.5	30				
	Alloy 3	Union Carbide[20]	12.5	Bal.	(+ 1 Si, 3 Be, 1 Mn)			2.4	3	—	30				
	Alloy 19	Union Carbide[20]	10.5	Bal.	(+ 1 Si, 3 Fe, 1 Mn)			1.7	3	—	31				
	Star J	Union Carbide[20]	17	Bal.	(+ 1 Si, 3 Fe, 1 Mn)			2.5	2.5	—	32				
	Rene' 41	Union Carbide General Electric	--	11	3.2	-	-	0.1	Bal.	10	20	Al 1.6 B 0.005 Fe 2.0			
	Astroloy	General Electric (12)		17	3.25	-	-	0.1	Bal.	5	15	Al 4.25 B .025 Fe 2.0	Good 1700°F Na		
	Fe	(42) (128)													
	Ni	(42) (128)													
	Co	(42) (128)													
B. Refractory Metals, Alloys	Cb-1Zr	DuPont, Wah Chang[41,64]	--	--	--	Bal.	--	-	--	--	--	Zr 1.0	Good 2200°F K	Stable	Stable
	AS-30	General Electric[42,43]	20	--	--	Bal.	--	0.10	--	--	--	Zr 1.0	Good 2000°F K	Stable	Stable
	TZM	Climax, Universal Cyclops[44,45]	--	--	0.5	--	--	0.04	--	Bal.	--	Zr 0.1	Good 2000°F K	Stable	Stable
	TZM (Nitride)														
	W	(128,140) (42,15)											Good 2000°F	Stable	Stable

TABLE III (Continued)

Materials Class	Material	Source	Composition W	Co	Ti	Cb	Ta	C	Ni	Mo	Cr	Other	Resistance to K Corrosion[16]	Estimated Stability in Cb-1Zr/K System[15] Mod. T.	Elev. T.
C. Fe-Co-Ni Bonded Carbides	K11	Kennametal[1-5]	90.5	2.5	--	--	--	5.97	--	--	--	--		Stable	Unstable
	K91	Kennametal[1-5]	71.4	20	--	.2	3.5	4.9	--	--	--	--			
	K96	Kennametal[1-5]	86.3	5.75	--	.3	1.8	5.77	--	--	--	--			
	K601	Kennametal[1-5]	84.5	--	--	--	10	5.5	--	--	--	--			
	779	Carboloy[6]	91WC	9	--	--	--	--	--	--	--	--	Good 1500°F Na		
	895	Carboloy[6]	94WC	6	--	--	--	--	--	--	--	--			
	999	Carboloy[6]	97WC	3	--	--	--	--	--	--	--	--			
	905	Carboloy[6]	93WC	3	--	--	4 TaC	--	--	--	--	--			
	907	Carboloy[6]	74WC	6	--	--	20 TaC	--	--	--	--	--	Good 1500°F Na		
	78	Carboloy[6]	76WC	8	12 TiC	--	4 TaC	--	--	--	--	--			
	330	Carboloy[6]	46WC	--	30 TiC	--	9.5 TaC	--	12	2	--	--			
	K138A	Kennametal[1-5]	--	20	TiC	CbC	TaC	--	--	--	--	--	Good 1500°F NaK		
	K150A	Kennametal[1-5]	--	--	73 (80 TiC)	10 CbC	--	17	10	--	--	--	Good 1500°F Na		
	K151A	Kennametal[1-5]	--	--	58 (70 TiC)	7.5 10 CbC	.5	15	19	--	--	--	Good 1500°F Na		
	K162B	Kennametal[1-5]	--	--	52 (64 TiC)	4.5 6 CbC	.3	13	25	5	--	--	Good 1500°F Na		
	608	Carboloy[6]	2	--	--	--	--		15	--	83 Cr_3C_2	--	Good 1500°F Na		
	5011	Carboloy[6]	82WC	--	--	--	--	--	16	--	2	--			
	Ferro-TiC C	Sintercast[32]	-	--	26	--	--	7	--	2	2	Fe Bal.		Unstable	Unstable
	Ferro-TiC J	Sintercast[33]	18	--	TiC	--	--	--	--	1	4	Fe Bal.		Stable	Unstable
	Ferro-TiC S-45	Sintercast[34]	--	--	39 TiC	--	--	--	7.3	--	11	Fe 42			
	Ferro-TiC S-55	Sintercast[34]	--	--	52 TiC	--	--	--	5.7	--	8.6	Fe 33			
D. Carbides	B_4C	Carborundum[7]											Fair 1500°F Na	Stable	Unstable
	B_4C	Norton[9,10]			B + C 98-99.5; (B_2O_3 0.2; Fe 0.5; Al 0.2; Ca 0.1; Mg 0.05) - Max.										
	B_4C + 31% TiB_2	Norton[9,10]													
	TiC	Carborundum[7]											Good 1500°F Na	Stable	Stable
	TiC	Norton[9,10]			77.84	--	--	19.56 (2.54 Free)	--	--	0.50 N 0.004 Fe		Good 950°K NaK		
	TiC (Fugitive Binder)	Kennametal[1-5]													

TABLE III (Continued)

Materials Class	Material	Source	Composition: W	Co	Ti	Cb	Ta	C	Ni	Mo	Cr	Other	Resistance to K Corrosion	Estimated Stability in Cb-1Zr/K System: Mod. T.	Elev. T.
D. Carbides (Cont'd)	ZrC	Carborundum [7]											Good 1500°F Na	Stable	Stable
	ZrC	Norton [9,10]	--	--	Trace	--	--	11.6	--	--	86.90 Zr 0.5 N Trace Fe		Good 1500°F Li, Na		
	Cr_3C_2	Norton [9,10]	--	--	--	--	--	14	--	--	83		Good 1500°F Na	Stable	Unstable
	TaC	Carborundum [7]												Stable	Stable
	TaC	Norton [9,10]	--	--	0.2 Max.		Ta + Cb 93.3-93.7	6.2-6.3 (0.1 Free)	--	--	0.1 Max. 0.05 Max. 0.2 Max.	Fe SiO_2 CaO			
	TaC (Fugitive Binder)	Kennametal [1-5]													
	HfC	Carborundum [7]													
	CbC	Carborundum [7]													
	CbC (Fugitive Binder)	Kennametal [1-5]													
E. Oxides	Al_2O_3 (Lucalox)	General Electric [11-13]	99.9 Al_2O_3										Good 1500°F Na	Stable	Stable
	Al_2O_3 (030)	Carboloy [6]													
	Al_2O_3	Zircoa	99.7 Al_2O_3 - 0.15 Max. SiO_2										Good 1000°F Na		
	ZrO_2 (Stabilized)	Zircoa [2,3]	(Proprietary)										Bad 1500°F Na		
	BeO (B-6)	Brush [25,26,28-31]	98.5 BeO; 0.0050 Si; 0.0060 Al; 0.0030 Na										Good 1500°F Na		
	Y_2O_3	Zircoa [24]	99.9 Y_2O_3												
F. Borides	CbB_2	Norton [9,10]												Stable	Stable
	ZrB_2	Carborundum [7]											Good 1500°F Na		
	ZrB_2	Norton [9,10]	--	--	0.33	--	--	0.75	0.27 Fe 0.02 N		78.23 20.20	Zr B			
	TiB_2	Carborundum [7]													
	TiB_2	Norton [9,10]	--	--	67.54	--	--	0.72	--	--	30.66 0.14 0.50	B Fe N			

TABLE III (Continued)

Materials Class	Material	Source	Composition W	Co	Ti	Cb	Ta	C	Ni	Mo	Cr	Other	Resistance to K Corrosion(16)	Estimated Stability in Cb-1Zr/K System(15) Mod. T.	Elev. T.
G. Refractory Metal Bonded Cermets	LT-1B	Union Carbide(22)	--	--	$_2TiO_2$	--	--	--	--	20	59	19 Al_2O_3		Stable	Unstable
	LT-2	Union Carbide(22)	60	--	--	--	--	--	--	--	25	15 Al_2O_3		Stable	Unstable
	TiC + 5% Mo	(123)												Stable	Stable
	TiC + 10% Mo	(123)													
	TiC + 20% Mo	(123)													
	TiC + 5% W	(123)													
	TiC + 10% W	(123)													
	TiC + 20% W	(123)													
H. Other Materials	TiN	Norton (9,10)	--	--	75.65	--	--	--	--	--	17.05	N	Bad 1500°F Na	Stable	Stable
	BN	National Carbon(8,7)	97 BN; 2.40 B_2O_3; Alk. Earth Oxides 0.10; Al_2O_3 + SiO_2 0.20; C 0.008										Bad 1500°F Na		
	BN	Carborundum(7,8)													
	Ta_2Be_{17}	Brush (27)													
	Ce_2S_3	American Potash (48)												Stable	Unstable
	CeS	National Carbon													Stable
	$MoSi_2$	(123)											Good 1500°F Na	Stable	Unstable
	Ti_5Si_3	(123)												Stable	Stable
	$CbSi_2$	(123)												Stable	Stable

TABLE IV: MECHANICAL AND PHYSICAL PROPERTIES OF CANDIDATE MATERIALS

Material	Density g/cc	Hardness R.T.	Hardness H.T.	R.T. Compressive Yield, ksi	H.T. Compressive Yield, ksi	R.T. Tensile Yield, ksi	H.T. Tensile Yield, ksi	R.T. Trans. Rupt, ksi	H.T. Trans. Rupt, ksi	R.T. Mod. of Elas. psi x 10^{-6}	H.T. Mod. of Elas. psi x 10^{-6}	Thermal Expansion in/in/^{o}F x 10^{-6}	Thermal Conductivity BTU/Ft^2/Ft/Hr/^{o}F	Wear $\frac{1}{\text{Volume Loss}}$
A. Nonrefractory Metals, Alloys														
Vasco-Hypercut		$(86_A)70_C$	$(1200F)41_C$											
Vantro-S		$(85_A)67_C$	$(800F)62_C$											
Vascojet MA-2		$(84_A)65_C$	$(800F)48_C$											
Vasco 1741		$(81_A)61_C$	$(800F)47_C$											
Vascomax 300 CVM	8.0	$(77_A)53_C$		317		290	(1000F)155	-	-	26.5	(900F)20	5.6	-	-
Rex 49	8.17	$(86_A)68_C$	(1250F) $67_A 32_C$	-	--	245 (56.5_C)	(800F)216	-	-	--	--	-	--	-
L-605	9.1	$(62_A)24_C$ (225 BHN)	(1472F) (120 BHN)	-	--	67	(1600F)36	-	-	32	(1600F)22	(RT-200F)6.8 (RT-1600F)9.06	RT-5.6 (1600F)15	-
L-605 Cold Reduced 20% and Aged	9.1	$(73_A)49_C$	--	-	--	204	(1200F).50 (1600F).55	-	-	-	--	(70-400F)7.19 (70-1600F)9.06	--	-
Alloy 6B	8.38	$(69\text{-}72_A)$ $38\text{-}44_C$	(1600F) 102-BHN	347	--	-	(1000F)102 (1600F)41	-	-	30	--	(32-572F)8.0 (32-1652F)9.4	RT-8.55	-
Alloy 3	8.64	$(81_A)60_C$ 580-BHN	(1652F) 160-BHN	310	--	85	--	213	-	33	--	(32-572F)7.1 (32-1600F)8.1	--	-
Alloy 19	8.36	$(78_A)55_C$ 512-BHN	(1652F) 134-BHN	310	--	110	--	244	-	39	--	(32-572F)7.6 (32-1652F)8.7	--	-
Star J	8.76	$(82_A)62_C$ 600-BHN	(1652F) 245-BHN	335	--	75	--	198	-	37	--	(32-572F)6.8 (32-1652F)7.9	--	-
Rene' 41	8.22	30_C	--	-	--	155	(1600F)82	-	-	31.6	(1600F)23	(RT-600F)7.2 (RT-1600F)8.9	RT-5.17 (1600F)14	-
Astroloy	7.9	70_A	(1500F) 68_A	-	--	136	(1600F)85	-	-	32.5	(1600F)24.3	(600F)7.5 (1600F)9.3	RT-4.6 (1600F)13.1	-
Fe	7.86	110-BHN	55-BHN(752F)	-	--	26.0-32.0	--	-	-	29.2	(850F)24.0	(RT-212F)6.5 (RT-1600F)8.5	RT-43.5 (1600F)17.0	-
Ni	8.90	210VHN	85VHN(932F)	-	--	(8.5 annealed) 40-90	--	-	-	30.0	(1400F)23.6	(RT-212F)7.4 (RT-1600F)9.4	RT-53.2 (932F)35.8	-
Co	8.85	125-BHN	--	122	--	31-65	--	-	-	30.0	(1600F)21.0	(RT-212F)6.8	RT-40.9	-

TABLE IV (Continued)

Material	Density g/cc	Hardness R.T.	Hardness H.T.	R.T. Compressive Yield, ksi	H.T. Compressive Yield, ksi	R.T. Tensile Yield, ksi	H.T. Tensile Yield, ksi	R.T. Trans. Rupt, ksi	H.T. Trans. Rupt, ksi	R.T. Mod. of Elas. psi x 10^{-6}	H.T. Mod. of Elas. psi x 10^{-6}	Thermal Expansion in/in/^oF x 10^{-6}	Thermal Conductivity BTU/Ft^2/Ft/Hr/^oF	Wear $\frac{1}{\text{Volume Loss}}$
B. Refractory Metals, Alloys														
Cb-1Zr	8.57	90-150VHN				22-65	(1200F)40			17		4.6		
Cb-1Zr (Nitride)														
AS-30	9.68	316VHN				143	(1600F)92					(RT-600F)4.4 (RT-1600F)4.8		
AS-30 (Nitride)														
AS-30 (Carburize)														
TZM	10.22	$(62_A)24_C$				105	(1600F)50			46	(1600F)36	(600F)3.0 (1600F)3.2	RT-68 (1600F)60	
TZM (Nitride)		1400 KHN												
W	19.3	Kg/mm^2 270	Kg/mm^2 70 (1832F)			180	(1600F)70			59.0	(1400F)54.4	(RT-212)2.8 (RT-1600F)3.0	RT-116	
C. Fe-Co-Ni Bonded Carbides														
K11	15.2	93_A		600				175		94		(RT-400F)2.75 (RT-1200F)2.75	(212F)69 (842F)52	300
K91	13.4	86_A		590	(1600F)60			375		69		(RT-400F)3.44 (RT-1200F)3.85	--	45
K96	14.9	92_A	(1400F)84_A	690	(1600F)250	205		250		92		(RT-400F)2.52 (RT-1200F)3.01	(212F)58 (842F)45	165
K601	15.3	94_A		680	(1600F)600			100		89		(RT-400F)2.93 (RT-1200F)3.40	(212F)39 (842F)35	675
779	14.6	89_A	(1400F)76_A	600				300		88		(RT-400F)2.71 (RT-1500F)3.23	(932F)	
895														
999	15.2	93_A		615				175		105		(RT-400F)2.22	(392F)69	
905	15.1	92_A		615				200		98		(RT-400F)2.22	(392F)58	
907	14.7	91_A	(1400F)79_A	705				215		86		(RT-400F)2.56	(392F)41	
76	11.8	92_A		625				195		78		(RT-400F)3.06	(392F)23	
330	9.0	91_A		520				200		65		(RT-400F)3.5 (RT-1500F)4.7		

TABLE IV (Continued)

Material	Density g/cc	Hardness R.T.	Hardness H.T.	R.T. Compressive Yield, ksi	H.T. Compressive Yield, ksi	R.T. Tensile Yield, ksi	H.T. Tensile Yield, ksi	R.T. Trans. Rupt, ksi	H.T. Trans. Rupt, ksi	R.T. Mod. of Elas psi x 10^{-6}	H.T. Mod. of Elas. psi x 10^{-6}	Thermal Expansion in/in/^oF x 10^{-6}	Thermal Conductivity BTU/Ft^2/Ft/Hr/^oF	Wear $\frac{1}{\text{Volume Loss}}$
C. Fe-Co-Ni Bonded Carbides (Cont'd)														
K138A	5.6	89_A		520	(1600F)150			150		59		(RT-400F)3.70 (RT-1200F)4.40	(212F)15 (842F)18	20
K150A	5.6	91_A						122						
K151A	5.8	89_A	(1400F)70_A	520	(1600F)155	110		150		58		(RT-400F)4.60 (RT-1200F)4.60	(212F)13 (842F)15	
K162B	6.0	89_A	(1400F)74_A	450	(1600F)175	112	(1600F)93	175		59	(1600F)4.8	(RT-400F)3.70 (RT-1200F)4.60	(212F)11 (842F)13	20
608	7.0	88_A	(1400F)79_A	500				113	(1500F)120 (1800F)100	50		(RT-400F)5.08 (RT-1500F)6.30	(932F)9.8	
5011														
Ferro-TiC C	6.6	$(86_A)70_C$		360				225-325		45		(RT-392F)4.6 (RT-1292F)5.4		
Ferro-TiC J	8.8	$(86_A)70_C$						250						
Ferro-TiC S-45	6.4	$(73_A)45_C$						280				(RT-1652F)6.9		
Ferro-TiC S-55	6.0	$(78_A)55_C$						270				(RT-1652F)6.0		
D. Carbides														
B_4C	2.5	3000 KHN						35		65		(RT-1832F)3.0	RT-15.5 (797F)47.5	
B_4C	2.5	2800 KHN		414				40		65		(32-1472F)3.1	RT-15.5	
B_4C + 31% TiB_2	2.8	2750 KHN		600				63	(2200F)55	66				
TiC	4.9	2500 KHN 93_A		109-190				33		67		(RT-1832F)4.9	RT-17.8	
TiC	4.9	2470 KHN		300				40		45		(32-1472F)4.2	RT-9.8	
TiC (Fugitive Binder)														
ZrC	6.7	2700 KHN 92_A		238		16		22		65		(RT-1832F)3.7	RT-11.8 (1832F)20.7	
ZrC	6.7	2090 KHN		238				40		50		(32-1472F)3.5	RT-11.8	

TABLE IV (Continued)

Material	Density g/cc	Hardness R.T.	Hardness H.T.	R.T. Compressive Yield, ksi	H.T. Compressive Yield, ksi	R.T. Tensile Yield, ksi	H.T. Tensile Yield, ksi	R.T. Trans. Rupt, ksi	H.T. Trans. Rupt, ksi	R.T. Mod. of Elas. psi x 10^{-6}	H.T. Mod. of Elas. psi x 10^{-6}	Thermal Expansion in/in/°F x 10^{-6}	Thermal Conductivity BTU/Ft^2/Ft/Hr/°F	Wear $\frac{1}{\text{Volume Loss}}$
D. **Carbides (Cont'd)**														
Cr_3C_2	6.6													
TaC	14.5	1950 KHN						31	(3532F)17.6	~76		(RT-1832F)3.6	RT-12.8	
TaC	14.6	1470 KHN								91		(32-1472F)3.5	RT-12.8	
TaC (Fugitive Binder)														
HfC	12.6	2600 KHN						35	(3532F)12	62		(RT-1832F)3.4	RT-12.8	
CbC	7.8	2400 KHN						35	(3532F)2.7	50+		(RT-1832F)3.9	RT-8.4	
CbC (Fugitive Binder)														
E. **Oxides**														
Al_2O_3 (Lucalox)	3.98	85_A						45		56		(RT-1652F)4.6	(212F)13+	
Al_2O_3 (030)	4.1	93_A	(1400F)84_A	600				90		58	(1832F)45.5	(RT-400F)3.4 (RT-1500F)4.3	(212F)15.6	
Al_2O_3				420	35.6 (2500F)	35.8	4.3 (2500F)	50.6	(2500F)2.3	52.4	(2500F)32.7	(RT-2200F)4.7	RT-10 (2000F)2.5	
ZrO (Stabilized)	5.8	58_C 8MoH		303	100 (2200F)	20	10 (2370F)			21.5	(1832F)12.5 (2370F)11.8	(RT-2200F)5.6	(2200F)55 (3200F)1.0	
BeO (B-6)	3.0	9MoH		114	20 (2200F)			30		39-45	(1832F)33 (2200F)20	(500F)4.4 (2200F)6.2	(400F)57 (800F)36 (600F)64 (1500F)26	
Y_2O_3	4.84											(400F).7 (1200F)2.8	> ZrO_2	
F. **Borides**														
CbB_2	6.5												RT-0.4 (392F)047-062	
ZrB_2	6.1	1560 KHN						66	(2000F)42	64		(RT-1832F)3.6	RT-13.3	
ZrB_2	6.0	1560 KHN		225				50		42		(32-1472F)2.5	RT-13.7	
TiB_2	4.5	2700 KHN						19		53		(RT-1832F)3.5	RT-14.5	
TiB_2	4.5	2710 KHN		325				50		80		(32-1472F)2.5	RT-14.5	

TABLE IV (Continued)

Material	Density g/cc	Hardness R.T.	Hardness H.T.	R.T. Compressive Yield, ksi	H.T. Compressive Yield, ksi	R.T. Tensile Yield, ksi	H.T. Tensile Yield, ksi	R.T. Trans. Rupt, ksi	H.T. Trans. Rupt, ksi	R.T. Mod. of Elas. psi x 10^{-6}	H.T. Mod. of Elas. psi x 10^{-6}	Thermal Expansion in/in/°F x 10^{-6}	Thermal Conductivity BTU/Ft^2/Ft/Hr/°F	Wear $\frac{1}{\text{Volume Loss}}$
G. Refractory Metal Bonded Cermets														
LT-1B	6.0	76_A		240				56	(1800F)54	38	(1832F)31	(RT-1832F)4.71	RT-19.3 (1832F)10.9	
LT-2	8.8	77_A						73	(1800F)67	38	(1832F)32	(RT-1832F)4.64		
TiC + 5% Mo	5.12						(1800F)21.7		(1600F)45					
TiC + 10% Mo	5.06						(1800F)24.6		(1600F)53					
TiC + 20% Mo	5.24						(1800F)16.4		(1600F)35					
TiC + 5% W	5.14						(1800F)25.3		(1600F)63					
TiC + 10% W	5.22						(1800F)20.6		(1600F)51					
TiC + 20% W	5.31						(1800F)14.3		(1600F)34					
H. Other Materials														
TiN	5.4	1770 KHN		141				34					RT-16.8	
BN	2.25	115 B 2MoH		27	(1380F)6.5	3.0	(1380F)1.0	16 -> 7 ↑	15-> 570F 7 ↑	12.4 -> 4.9 ↑	8.79 -> 570F 3.47 ↑ 1.54 ->1300F 0.5 ↑	5.6 ->RT-660F 0.33↑ 4.48->RT-1300F 0.49↑	8.8 -> 570F 16.6 ↑ 7.7 ->1300F 15.6 ↑	
BN	2.2	Soft						5.0		13.0		(RT-1472F)2.1		
Ta_2Be_{17}	5.0	1120 VHN		190	(1600F)150			30	(1600F)40	47	(1600F)40	(RT-800F)6.7 (RT-1600F)7.7		
Ce_2S_3	5.2	447 VHN										(212F)7.3		
CeS	5.9	257 VHN										(212F)5.4		
$MoSi_2$	8.97	1290 Kg/mm^2		100-350										
Ti_5Si_3		986 Knoop												
$CbSi_2$	5.29	1050 Kg/mm^2												

TABLE V: PRODUCIBILITY OF CANDIDATE MATERIALS

	Material	Producibility	Method of Consolidation	Special Remarks
A. Nonrefractory Metals, Alloys	Vasco-Hypercut	Excellent	Air Melted Electrodes + Vacuum Arc Melting	$1000^{o}F$ Max. Use Temperature
	Vantro-S			$1000^{o}F$ Max. Use Temperature
	Vascojet MA-2			$1000^{o}F$ Max. Use Temperature
	Vasco 1741			$600^{o}F$ Max. Use Temperature
	Vascomax 300 CVM			$1000^{o}F$ Max. Use Temperature
	Rex 49		Air Melt	$1000^{o}F$ Max. Use Temperature
	L-605		Air Melt + Work	
	L-605 Cold Reduced 20% and Aged		Air Melt + Work + Age	
	Alloy 6B		Chill Cast	
	Alloy 3		Chill Cast	
	Alloy 19		Chill Cast	
	Star J		Chill Cast	
	Rene' 41		Vacuum Arc Melt + Work	
	Astroloy		Vacuum Arc Melt + Work	
	Fe		Air Melt + Work	
	Ni			
	Co			
B. Refractory Metals, Alloys	Cb-1Zr	Excellent	Vacuum Arc Melt or EB Melt + Work	
	AS-30	Very Good	Vacuum Arc Melt + Work	
	TZM	Excellent	Vacuum Arc Melt + Work	
	W	Very Good	Vacuum Arc Melt + Work	

TABLE V (Continued)

	Material	Producibility	Method of Consolidation	Special Remarks
C. Fe Co-Ni Bonded Carbides	K11	Very Good	Powder Met. Cold Press + Sinter or Hot Press	
	K91			
	K96			
	K601	Good		
	779	Very Good		
	895			
	999			
	905			
	907			
	78			
	330			
	K138A			
	K150A			
	K151A			
	K162B			
	608			
	5011			
	Ferro-TiC C	Very Good	Cold Press + Sinter	$400^{\circ}F$ Max. Use Temperature
	Ferro-TiC J			$1000^{\circ}F$ Max. Use Temperature
	Ferro-TiC S-45			
	Ferro-TiC S-55			
D. Carbides	B_4C	Good	Powder Met. Hot Press	
	B_4C + 31% TiB_2	Good		
	TiC	Good		Dissolves in Alkaline Oxidizing Melts.
	TiC (Fugitive Binder)	Good	Cold Press + Sinter	

TABLE V (Continued)

	Material	Producibility	Method of Consolidation	Special Results
D. Carbides (Cont'd)	ZrC	Good	Powder Met. Hot Press	
	Cr_3C_2	↓	↓	Attacked by KOH, KNO_3
	TaC	Fair		
		Fair		
	TaC (Fugitive Binder)	Good	Cold Press + Sinter	
	HfC	-	Powder Met. Hot Press	
	CbC	-		
	CbC (Fugitive Binder)	Good	Cold Press + Sinter	
E. Oxides	Al_2O_3 (Lucalox)	Very Good	Cold Press + Sinter	
	Al_2O_3 (030)	↓		
	Al_2O_3		Hot Press, Slip Cast	
	ZrO_2 (Stabilized)	Very Good	Cold Press + Sinter or Slip Cast	
	BeO (B-6)	↓	Cold Press + Sinter	Toxic; Dissolves in Alkali CO_3, Fused Alkalies
	Y_2O_3	-		
F. Borides	CbB_2	Good	Powder Met. Hot Press	
	ZrB_2	↓	↓	
	TiB_2			

TABLE V (Continued)

	Material	Producibility	Method of Consolidation	Special Remarks
G. Refractory Metal Bonded Cermets	LT-1B	Very Good	Slip Cast	
	LT-2	Very Good	Slip Cast	
	TiC + 5% Mo	Unknown	Powder Met. Hot Press or Cold Press + Sinter	
	TiC + 10% Mo			
	TiC + 20% Mo			
	TiC + 5% W			
	TiC + 10% W			
	TiC + 20% W			
H. Other Materials	TiN	Fair	Powder Met. Hot Press	Decomposed by Fused Alkali Solution; High Vapor Pressure with Respect to Refractory Compounds
	BN	Good		Vapor Pressure High
	Ta_2Be_{17}			
	Ce_2S_3	Very Good		
	CeS	Very Good		
	$MoSi_2$	Good	Hot Press	Decomposed by Fused Alkalies
	Ti_5Si_3		Hot Press	
	$CbSi_2$		Hot Press	

TABLE VI: THERMOCYNAMIC DATA FOR VARIOUS COMPOUNDS
(Values for ΔH and ΔF in kcal; for ΔS in Cal/°C)

Materials	$-\Delta H_{298}$	ΔS_{298}	$-\Delta F_{300}$	$-\Delta F_{500}$	$-\Delta F_{1000}$	$-\Delta F_{1500}$
Carbides						
$1/2Cr_3C_2$	10.5[a]	10.2[a]	10.6[a]	10.7[a]	11.4[a]	12.2[a]
TaC	38.5[a]	10.1[a]	38.1[a]	37.9[a]	37.3[a]	36.8[a]
TiC	43.9[a]	5.8[a]	43.0[a]	42.5[a]	41.3[a]	39.9[a]
ZrC	44.1[a]	9.3[c]	43.4[a]	43.0[a]	41.9[a]	40.8[a]
HfC	44.7[b]	10.91[b]	44.3[b]	44.1[a]	43.4[a]	42.6[a]
CbC	33.7[a]	----	----	----	----	----
WC	9.1[a]		9.0[a]	8.9[a]	8.7[a]	8.5[a]
B_4C	14.0[a]	6.47[a]	13.9[a]	13.8[a]	13.5[a]	13.3[a]
	12.2[c]	----	----	----	----	----
$1/4KC_4$	0.95[j]	----	----	----	----	----
Nitrides						
2BN	128.4[a]	7.34[a]	188.2[c]	99.8[c]	78.6[c]	57.8[c]
2CbN	113.6[a]	----	100.0[j]	90.8[j]	----	----
2TiN	160.8[a]	14.4[a]	147.2[a]	138.4[a]	116.2[a]	93.6[a]
2ZrN	174.6[a]	18.6[a]	160.6[a]	151.8[a]	129.4[a]	106.6[a]
$2Cb_2N$	122.2[e]	----	----	----	----	----
$2K_3N$	35.0[j]	----	----	----	----	----
Oxides						
$2/3Al_2O_3$	266.6[a]	8.2[a]	251.6[a]	241.6[a]	216.4[a]	182.0[a]
2BeO	286.2[a]	6.7[d]	272.6[a]	263.4[a]	240.8[a]	218.6[a]
ZrO_2	259.5[a]	12.1[a]	245.5[a]	236.2[a]	213.8[a]	191.9[a]
$2/3Y_2O_3$	303.6[a]	15.8[a]	289.4[a]	280.2[a]	257.6[a]	236.0[a]
KO_2	67.7[a]	27.9[a]	59.3[i]	53.8[i]	39.8[i]	25.8[i]
$2K_2O$	172.8[a]	----	153.2[a]	141.0[a]	109.6[a]	78.0[a]
TiO_2	225.5[a]	12.0[a]	205.9[a]	197.6[a]	176.7[a]	155.9[a]
$2/5Cb_2O_5$	181.6[a]	13.2[a]	168.8[a]	160.2[a]	----	----
CbO_2	190.9[a]	13.03[a]	177.5[a]	168.5[a]	146.2[a]	123.8[a]
2CbO	195.0[a]	----	----	176.6[a]	157.4[a]	----
2TiO	247.8[a]	16.6[a]	231.8[a]	223.4[a]	202.0[a]	180.8[a]
Sulfides						
2CeS	236.0[a]	----	255.0[a]	247.0[a]	227.0[a]	207.0[a]
$2/3Ce_2S_3$	200.2[a]	----	----	----	----	----
	200.4[d]	----	----	----	----	----
$2K_2S$	204.8[a]	----	190.0[j]	----	----	----
Borides						
$1/2CbB_2$	29.5[f]	----	----	----	----	----
	18[g]	----	----	----	----	----
	17[h]	----	----	----	----	----
$1/2ZrB_2$	36[c]	----	----	----	----	----
$1/2TiB_2$	35[c]	----	----	----	----	----

Material	$-\Delta H_{298}$	$-\Delta H_{298}$
Silicides		
$1/2TiSi_2$	16.1 ± 4[k]	15.4-34.9[k]
TiSi	31.0 ± 4[k]	15.4-65.8[k]
$1/3Ti_5Si_3$	46.2 ± 3[k]	20.0-86.1[k]
ZrSi	37.0 ± 4[k]	58.0 ± 10[k]
$1/2ZrSi_2$	19.0 ± 4[k]	30.5 ± 5[k]
$1/3Zr_5Si_3$	46.0 ± 4[k]	72.0 ± 10[k]
$1/2Zr_3Si_2$	46.0 ± 6[k]	70.0 ± 10[k]
Zr_4Si	52.0 ± 6[k]	76.0 ± 10[k]
$1/2CbSi_2$	15.0 ± 7[k]	8.5-28[k]
$1/3Cb_5Si_3$	21.0 ± 10[k]	8.5-63[k]
Cb_2Si	21.0 ± 10[k]	----
$1/2TaSi_2$	13.1 ± 3[k]	12.8-32.3[k]
$1/3Ta_5Si_3$	28.9 ± 4[k]	----
Ta_2Si	30.7[k]	20.0-90.1[k]
Ta_5Si	32.2 ± 4[k]	----
$1/2MoSi_2$	13.6 ± 4[k]	5.8-15.5[k]
$1/3Mo_5Si_3$	22.0 ± 3[k]	----
Mo_3Si	21.0 ± 5[k]	20.0[k]

[a] Smithells, Colin J., Metals Reference Book, vol. 2, Butterworth, Inc., Washington, D.C., 1962.

[b] Thomas, D. E., and Hayes, E. T., "Metallurgy of Hafnium (1960), United States Government Printing Office, Washington 25, D.C.

[c] Dow Chemical Company, JANAF Thermochemical Tables, Midland, Michigan, 1963.

[d] Quill, L. L., "The Chemistry and Metallurgy of Miscellaneous Materials," Thermodynamics, McGraw-Hill, New York, 1950.

[e] Campbell, I. E., High Temperature Technology, Wiley, New York, 1956.

[f] Samsonov, G. V., "Heats of Formation of the Borides of Some Transition Metals," Zhurnal Fizicheskoi Khimii, p. 2057 (1956).

[g] Brewer, L., and Haroldsen, H., "The Thermodynamic Stability of Refractory Borides," Journal of Electrochemical Society, vol. 102, p. 399, 1955.

[h] Kubaschewski, O., and Evans, E., Ll. Metallurgical Thermochemistry, Pergamon Press, London, 1956.

[i] Calculated $-\Delta F_T = \Delta H_{298} - T\Delta S_{298}$

[j] Elliott, J. F., Thermochemistry for Steelmaking, vol. 1, Addison-Wesley Publishing Company, Inc., Massachusetts, 1960.

[k] Samsonov, G. V., Silicides and Their Uses in Engineering, FTD-TT-61-409/1 + 2, January 29, 1962.

[l] Brewer, L., and Krikorian, O., "Reactions of Refractory Silicides with Carbon and Nitrogen," Journal of Electrochemical Society, vol. 103, p. 38, 1956.

TABLE VII: MATERIALS RECOMMENDED FOR EVALUATION

A. Nonrefractory Metals and Alloys	Star J (Co Base Superalloy) Vasco Hypercut/Vantro S (Fe Base, High Strength Steels) Fe Co Ni Cu
B. Refractory Metals and Alloys	AS-30 (High Strength, Cb Base Alloy) Cb-1Zr TZM (Mo Base Alloy) W
C. Fe-Ni-Co Bonded Carbides	K601 (Binderless WC, TaC) 779 (9% Co Bonded WC) 999 (3% Co Bonded WC) 907 (6% Co Bonded WC, TaC) 330 (12% Ni Bonded WC, TiC, TaC) K138A (20% Co Bonded TiC, CbC, TaC) K150A (10% Ni Bonded TiC, CbC) K162B (25% Ni Bonded TiC, CbC)
D. Carbides	TiC ZrC TaC
E. Oxides	Al_2O_3 (Lucalox or 030) ZrO_2 (Hard) Y_2O_3 BeO
F. Borides	TiB_2
G. Refractory Metal Bonded Cermets	TiC + 5W TiC + 10Mo TiC + 10Cb Classified Composition
H. Other Materials	TiN CeS $MoSi_2$ $CbSi_2/Ti_5Si_3$ Ta_2Be_{17}

preclude this. Then, using relatively simple and reliable surface treatments which would enhance the bearing characteristics of a metallic shaft material could be advantageous. For example, the surface layers of refractory alloys can be substantially hardened by the internal action of reactive alloying elements with the interstitial elements. Although modifying the surface composition of metallic materials tó improve friction and wear characteristics warrant investigation, because of the complexity of the composite and the need to obtain base line data initially, it currently exceeds the scope of the program.

Material Class A: Nonrefractory Metals and Alloys

As a broad class, the nonrefractory metals, superalloys and high strength steels, have lower temperature limitations than the materials in the other classes considered for the program. However, these materials exhibit many attractive combinations of properties, and representative candidates should be considered for inclusion in the program. With these materials, it is possible to achieve high strength and hardness and yet retain measurable ductility and the ability to deform plastically: They are resistant to corrosion by potassium, although to varying degrees with temperature; solubilities between pairs are known or can be predicted from crystal structure and difference in atomic size; because of their method of consolidation, properties are reproducible and a minimum of porosity is attainable.

From a strength standpoint, the nickel and cobalt base superalloys have the highest temperature potential in this class. The use temperature, however, must be consistent with their stability in a columbium/potassium system. Star J was selected to represent the superalloys for the following reasons:

(1) Cobalt-base alloys have demonstrated more superior corrosion resistance in alklai metals than nickel-base alloys.

(2) The massive amount of precipitate [$Ni_3(Al,Ti)$] in the high strength nickel alloys will probably engender greater dimensional instability over the cobalt-base alloys.

(3) Star J has the highest hardness, R_c62, of the superalloys reviewed.

(4) Cobalt alloys have a higher elastic modulus, than nickel alloys, i.e., 37 x 10^6 psi versus 32 x 10^6 psi.

(5) Actual bearing experience and data are available on Star J for comparative purposes.

The high strength, iron base, heat-treatable steels represent the hardest materials of the metal alloys reviewed. Of these, the type typified by Vasco-Hypercut and Vantro S have the highest hardness, R_c 70 and R_c 67, respectively, at room temperature. Because of an overtempering mechanism, however, the maximum use temperature for these alloys is below 1000°F where the resistance to corrosion by potassium,[84] dimensional stability[37,39] and hot hardness (R_c 62 to 800°F for Vantro S) is considered good.

In addition to the superalloy and high strength steel, iron, nickel, cobalt and copper were recommended for inclusion so that the program would be as versatile as possible with respect to the selection of pairs. For example, it has been established[78] that iron, nickel, cobalt do not wet Al_2O_3 (low work of adhesion) and that no reaction occurred between nickel and Al_2O_3 at 1800°C.[126] The carbide producers have confirmed that nickel and cobalt have little solubility in WC or TiC. Also, negligible solubility is reported for iron in TiN[127] and for copper in WC or tungsten.[76] Additionally, excellent wear-in characteristics for copper against tungsten and Carboloy (cobalt bonded WC) in NaK are reported by Coffin;[76] it would be desirable to reproduce this behavior with equipment in this program.

Materials Class B: Refractory Metals and Alloys

Except hardness, many of the advantages offered for the nonrefractory metals and alloys in Class A are true also for the refractory metals and alloys. The hot hardness values for the refractory metals at the pertinent bulk temperatures are considerably lower than those for the high strength steels or Star J. However, if excessive interfactial temperatures should occur, the hot hardness and strength of the high melting point refractory metals would be superior.

The excellent resistance of the refractory metals and alloys to corrosion by potassium has been demonstrated at temperatures of approximately 2000°F, which surpasses the bulk temperature range relevant to this program. Also, the refractory metals tungsten, tantalum and molybdenum are expected to be stable in potassium in the presence of a columbium alloy at temperatures of approximately 1600°F.

Dr. L. Coffin* has suggested that the dispersed phases, which are stable in the refractory alloys and which provide creep

*Dr. L. Coffin, Research Laboratory, General Electric Company, is consultant for this program.

resistance, be considered as the second material in bearing combinations with the refractory alloy or metal. For example, TiC, ZrC, ZrO_2 would have little solubility in the refractory metals at temperatures of 1600°F.[129] Molybdenum has shown no reaction with Al_2O_3 at 1800°C.[126] Of the refractory metals and alloys reviewed, tungsten, TZM, Cb-1Zr and AS-30 alloys were recommended for selection. Unalloyed tungsten was chosen intentionally to provide base line data and to evaluate previously developed theories over a wide range of temperature. The TZM molybdenum alloy was selected because it has the highest strength and recrystallization temperature of the commercially available alloys and because the titanium and zirconium in the alloy may possibly be beneficial from a corrosion standpoint. Also, indications are that the properties (strength, ductility) of the alloy are more reproducible than the Mo-0.5 Ti alloy. The TZC alloys (titanium-zirconium-carbon) are stronger in creep than TZM but are not significantly harder, and they are very much in the development stage.

Two columbium alloys, Cb-1Zr and AS-30, were recommended since there is a significant difference in their hardness, i.e., approximately 100 VHN versus 315 VHN. Although F-48, a high strength columbium alloy, is suitable, there have been indications that the thermal stability of AS-30 is superior to that of F-48 alloy with respect to low temperature ductility.[130] Tantalum was omitted because of its chemical (corrosion) and mechanical (hardness) similarity to columbium. If an evaluation of tantalum becomes necessary, however, a tantalum alloy containing an internal getter, e.g., zirconium or hafnium, should be selected.

Material Class C: Iron, Nickel, Cobalt Bonded Carbides

The commercially produced cemented carbides were considered for the program because of their demonstrated good resistance to corrosion by sodium;[68,69] their excellent commercial status;[1,6] and their excellent mechanical and thermal properties, i.e., high compressive strength, hardness, elastic modulus, thermal conductivity and low thermal expansion (Table IV). Also, low porosity is achieved through liquid phase sintering action. Other investigators have shown promising results with these materials in sliding friction studies. Apkarian found Carboloy 779 and 55A to behave well under conditions of boundary lubrication at 750°F with NaK;[80] Kumpitsch found a number of combinations that showed low friction values in NaK-77 at temperatures to 1370°F, i.e., Carboloy 779 versus K149, HT77 versus K138, K84 versus K138A and HT77 versus K151A.[81] The cemented carbides that were selected were chosen for their binder content (amount and chemistry), lack of binder, mixed carbide content and type of carbide (WC, TiC, CbC, TaC); these factors influence the hardness, strength, thermal conductivity, thermal expansion and, probably, the corrosion resistance. The major limitation imposed by these materials is the anticipated lack of stability of the binder phase and of the WC in potassium in the presence of Cb-1Zr alloy as the temperature is increased. The materials that were recommended and the major variables to be evaluated are:

Material	Major Binder	Remarks
K601 (WC, TaC)	None	Maximum strength, hardness, corrosion resistance of WC cermets and minimum wear
779 (WC)	9% Cobalt	
999 (WC)	3% Cobalt	High thermal conductivity, low thermal expansion
907 (WC)	20% TaC 6% Cobalt	High strength
330 (WC)	30% TiC 9.5% TaC 12% Nickel	Complex carbides
K138A (TiC, CbC, TaC)	20% Cobalt	No WC
K150A (TiC, CbC)	10% Nickel	No WC
K162B (TiC, CbC)	25% Nickel	No WC

Material Class D: Carbides

The carbides of the transition metals IVA, VA and VIA (as well as the nitrides, borides and silicides) have many of the properties considered desirable for application in journal bearings. They exhibit thermal conductivity properties that are similar to those of pure metals; they have high hardnesses, high compressive strengths, high elastic moduli, high melting points; and they have demonstrated good resistance to corrosion.[69] In fact, the carbides are among the few materials resistant to corrosion by lithium. Because of their metallic nature, it has been suggested that Hume-Rothery's rules for alloying can be applied to predict solid solubilities. Also, Hagg's rule for interstitial element compounds must be considered in predicting solid solubility because of the influence of crystal structure on the degree of solubility attainable.[92] Again, this will be considered important in the selection of pairs for sliding contact studies. In this regard, most of the monocarbides have cubic crystal structures[123] and favorable atomic size differences and are completely miscible. The Mo_2C and WC have a hexagonal structure and, in general, have limited solubilities in the cubic carbides. Titanium carbide (TiC) forms a complete series of solid solutions with TiN and TiO, making pure TiC difficult to produce. Titanium carbide (TiC) has no solubility in Al_2O_3[92] but is soluble in TiB_2.

Of the carbides reviewed, TiC, ZrC and TaC were selected for consideration. Although B_4C is reported to be the hardest of all compounds,[9] 3000 KHN, it is extremely sensitive to thermal shock and would probably be thermodynamically unstable in a columbium/potassium system. This would also be true for Cr_3C_2 and WC. Recognizing that the properties of HfC and CbC are so similar to those of ZrC and that more processing experience has been acquired with ZrC, of the three carbides, only ZrC was recommended for evaluation. The carbide TaC was included because of its reported lower hardness and its higher elastic modulus. The primary concern associated with the binderless pure compounds is the inability to achieve high density (approaching 100% theoretical), which will result in a rough surface. Most of the production experience has been with TiC and compacts with the least amount of porosity will probably be achieved with this material.

Material Class E: Oxides

From the standpoint of journal bearing application, the ceramic oxides, like the refractory hard metal compounds, have many properties that are attractive. They have high hardnesses, high strengths, high elastic moduli, and they are expected to be resistant to corrosion by potassium and stable (Table VI) in a columbium alloy/potassium system. Beryllium oxide (BeO) was resistant to corrosion by sodium at 750°C;[68] Al_2O_3, at 500°C.[78] Data for ZrO_2 in sodium at 1500°F[69] show it to be poor only from the standpoint of dimensional change, which is probably caused by the instability of the crystallographic structure, i.e., improperly stabilized. From the consideration of material combinations, the oxide combinations have high adhesive strengths;[79] BeO has a tendency to react with other oxides.[123] As mentioned previously, good combinations may be expected for iron, nickel, cobalt,[78] molybdenum,[126] and TiC[79] against Al_2O_3.

Of the oxides reviewed, Al_2O_3 (Lucalox or 030), ZrO_2 (stabilized), Y_2O_3, and BeO should be considered. From the data, highest strengths (compression and elastic moduli) were reported for the 030 Al_2O_3 ceramic; the lowest compressive strength, 114 ksi, was reported for BeO. No strength data were found for Y_2O_3. In addition to their good mechanical properties, Al_2O_3 (Lucalox or 030) and ZrO_2 are produced readily to high theoretical densities with relatively low porosity. The Y_2O_3 and BeO were recommended for specific reasons. The first, Y_2O_3, is essentially immiscible in columbium and, in view of Coffin's theories on sliding surfaces,[76] this combination should be investigated. The latter, BeO, was recommended because of its high thermal conductivity.

Material Class F: Borides

The general observations made for the carbides, Material Class D, also apply to the borides. Consequently, they should also be considered for evaluation in the program. Compared to the carbides and oxides, generally, less information was found for the borides, i.e., no corrosion data. The TiB_2 and ZrB_2 have hexagonal crystal structures and are mutually soluble. From thermodynamic considerations, both TiB_2 and ZrB_2 are apparently more stable than CbB_2. Also, it is reported[123] that the TiB_2 is more stable than TiC and that generally the borides are more stable than the corresponding carbide or silicide. Good strengths and exceptionally high hardnesses, 2700 KHN, are reported for TiB_2 in contrast to a hardness of 1560 KHN for ZrB_2. Little data was found for CbB_2. For these reasons, $\underline{TiB_2}$ was recommended for study.

Material Class G: Refractory Metal Bonded Cermets

The refractory metal bonded cermets probably have the best potential as materials for potassium lubricated journal bearings in advanced space power systems. These materials should possess the corrosion resistance and the necessary chemical stability in a columbium alloy/potassium system. At the same time, like the nickel and cobalt bonded cermets, they should achieve the higher densities (lack of porosity) and superior ductilities than the pure compounds. However, few compositions are reported in the unclassified literature and there is very limited data available on their mechanical behavior. In bonding experiments with TiC,[123] only molybdenum and tungsten exhibited tendencies for good bonding. Although columbium and vanadium indicated poor bonding characteristics, the experimental hot pressing conditions may have contaminated the more reactive metals and inhibited diffusion. Of the series of cermets in the W-TiC and Mo-TiC system, the <u>10%Mo-TiC</u> and <u>5%W-TiC</u> compositions had the highest strength and were recommended in order to check the reference in the literature.

A number of complex refractory metal bonded cermets are reported in the classified literature. Particularily good results were achieved with one cermet, and, although of less interesting composition, it is recommended for evaluation in the program. In general, little experience has been acquired with this class of materials in industry and it may require a supplementary developmental investigation to assure that only high quality, i.e., high density, strength, materials are evaluated.

Material Class H: Other Materials

Additional materials that may prove suitable for application in potassium lubricated journal bearings or interesting from an experimental standpoint, i.e., hardness, chemistry, etc., are the nitrides, silicides, sulphides and beryllides.

As mentioned previously, the nitrides and silicides of the groups IVA, VA and VIA metals are metallic in nature, and, therefore, in the absence of phase diagrams, it may be possible to predict the compatibility between pairs. The nitrides have a cubic crystal structure and, where atomic sizes are favorable, they are soluble in each other and with the cubic carbides, e.g., TiC. Iron is not soluble in TiN. The nitrides as a class do not appear as promising[123] as the borides or carbides in that their vapor pressures are high; reactions have been reported between TiN and MgO; the metals and carbides decompose BN at high temperatures; they are generally softer and it is difficult to produce sound bodies. However, because of difference in chemistry, it is recommended that a nitride be included in the program. Thermodynamic data, Table VI, would indicate that the nitrides of interest are stable in the presence of columbium. The low hardness of BN is of interest for a soft-hard combination but its extreme anisotropy and low strength eliminated it from contention at this time. From a producibility standpoint, TiN is preferred rather than ZrN. Based on these considerations, TiN was recommended for evaluation.

Other than coatings for oxidation resistance, little information is available on the silicides. In contrast to the other hard metal compounds, the crystal structure of the silicides varies with the different transition metal groups. Although entropy data were not found, Table VI, estimations from heats of formation suggest that Ti_5Si_3 would be stable in the presence of columbium. Low heats of formation were found for $TaSi_2$, $MoSi_2$, $TiSi_2$ with respect to $CbSi_2$. Good resistance to corrosion by sodium has been reported for $MoSi_2$ at 1500°F and good chemical stability in general is reported for the silicides as a class.[76] Also, the main experience in the production of silicides is with the $MoSi_2$ for heating elements. Consequently, $MoSi_2$ and either Ti_5Si_3 or $CbSi_2$ were recommended for consideration. More producibility data will have to be obtained to determine which of the latter should be selected.

Recent experience has shown that Ta_2Be_{17} has promising properties, i.e., high compressive strength and high elastic modulus combined with a relatively moderate hardness, 1120 VHN.[27] Also CeS, is of interest because of its high negative free energy of formation, low vapor pressure, and low hardness, i.e., 257-477 VHN, for possible soft-hard combinations.

IV. MATERIALS PROCUREMENT

Bearing Materials

To achieve reliable bearing operation, attaining uniformity of certain critical properties in the production of bearings from batch to batch or heat to heat is of paramount importance. Changes in chemistry and processing procedures, which will affect the dimensional stability and/or strength and hardness of the material, or the unintentional addition of impurities, which will affect the surface chemistry, could have serious effects on the performance of bearings made from the material. For example, Chang has shown that large variations in strength and ductility of both columbium and molybdenum alloys are possible by changing either processing temperatures or final heat treatment.[129] If not properly controlled, the quality of the heat treating or sintering environment will affect the surface chemistry, e.g., contamination by oxygen, nitrogen and possibly carbon, and is an important consideration from the standpoint of mechanical behavior and resistance to corrosion. In the preparation of powder compacts, variables such as the particle size, shape, and distribution, purity of the raw materials, and sintering temperatures will affect the density of the product. This, in turn, will affect properties important for bearing operation, e.g., strength, hardness, coefficient of friction and dimensional stability.

These considerations necessitate understanding and documenting, in varying degrees for each class of materials, the history of the processing and fabrication procedures employed in the preparation of specimens for this program. The information is required not only for reproducibility but also as an aid in interpreting the results of the various phases of the investigation.

In general, reliable commercial sources with experience with the pertinent material will be utilized. In the procurement of materials from Classes A and B (metals and alloys), Class C (cemented carbides) and a few materials from Classes D, E, F and H (compounds such as Al_2O_3, ZrO_2), a uniform product should be obtainable because of their commercial status; procurement should be made against a fairly restrictive specification. Of these materials, it is generally accepted, however, that greater uniformity will be obtainable with the wrought materials of Classes A and B, which are produced from large heats ranging from 300 to 10,000 pounds, rather than with materials produced from small batches of powders.

Procuring certain other materials in Classes D, E, F and H and all the materials in Class G (refractory metal bonded cermets) will be considerably more difficult. Because these materials have not been made in large quantities for either bearing or metal cutting applications, there is insufficient documentation on the ability to produce a consistent product; therefore, the specifications for these materials will, of necessity, be less restrictive. In addition, it is expected that Class G materials will require a limited amount of development work to provide some assurance that high quality test or bearing configurations can be fabricated. Such an investigation, if necessary, will be executed by the vendor and will employ commercially available powders of known purity, particle size and distribution and existing consolidation/sintering facilities. The conditions of temperature, pressure and time of pressing, sintering temperature and the particle size and distribution of the starting blend that produces the maximum density and strength of the product will be selected for the production of the material for evaluation in the program. The resulting microstructure will be documented for future reference.

All vendors selected to participate in the program will be required to maintain and file all data pertaining to the raw material, processing and fabrication procedures that are used in the preparation of the finished product. Much of the processing data, because of its highly proprietary nature, will not be released. However, with the cooperation of the vendors and from data generated on the mechanical, chemical and physical behavior of the materials, preparing meaningful specifications for these materials should be possible at the conclusion of the program.

To assure that the incoming materials have suitable quality for use in the program, selected samples will be subjected to the following tests by the vendor and/or General Electric:

1) Microscopy
2) X-ray Diffraction
3) Chemical Analyses
4) Hardness
5) Density
6) Weight Measurement
7) Dimensional Measurement
8) Radiographic/Ultrasonic Inspection
9) Fluorescent Penetrant Inspection
10) Surface Roughness
11) Tensile/Transverse-Rupture

From these tests, information regarding the purity of the material, surface characteristics, porosity, crystal structure and microstructure will be acquired. Some of the data will also be used for later comparison with tested specimens.

Corrosion Capsule Materials

Purchase orders were placed for the Cb-1Zr mill products required for the fabrication of the corrosion test capsules. These orders included: one hundred feet of 1.00-inch OD x 0.080-inch thick wall tubing for capsule bodies; eleven feet of 0.080-inch thick x 4.00-inch wide sheet for end caps; fifty feet of 0.062-inch diameter wire for filler material required for the manual TIG welding of the bottom end cap; four hundred feet of the 0.062-inch diameter wire to be used in the fabrication of spacers and holders for the proper positioning of test specimens within the capsules.

The tubing was ordered from the Wah Chang Corporation, Albany, Oregon, to SPPS Specification 2A, "Seamless Tubing: Columbium - 1% Zirconium Alloy," with a promised delivery date of August 30, 1963. The sheet stock and wire were purchased from Kawecki Chemical Company, Boyertown, Pennsylvania, for delivery in early August. The 0.080-inch thick sheet is to be produced to SPPS Specification 1A, "Bar, Rod, Sheet, Plate and Strip: Columbium - 1% Zirconium Alloy," and the 0.062-inch diameter wire, to the chemical requirements only of SPPS Specification 1A.

Since Kawecki did not, at the time the order was placed, possess the ultrasonic equipment required by the specification for the proper inspection of the sheet, the facilities of Automation Industries, Incorporated, Columbus, Ohio, were used. The longitudinal beam inspection divulged several areas of severe defects, clearly visible in the autographic plots of the longitudinal beam scans shown in Figure 1, in plates G and J. The smaller sample in each photograph is the standard specimen that had been drilled with the holes required in the calibration of the equipment. The extraneous scans are traces of the structure supporting the plates for immersion in the water-filled inspection tank. Interestingly, the first trace of plate C showed two small indications (circled on the photograph); however, visual inspection of the plate revealed two small air bubbled located at the sites of the indications. The bubbles were brushed away and the second trace of plate C showed no defects, verifying the sensitivity of the equipment. Plates A, B, C, D, E, F, H and J were accepted by the General Electric Company for inclusion in the program. Sufficient stock will be sectioned from plate J to assure that the small defective area is discarded. Plate G will be replaced by the vendor.

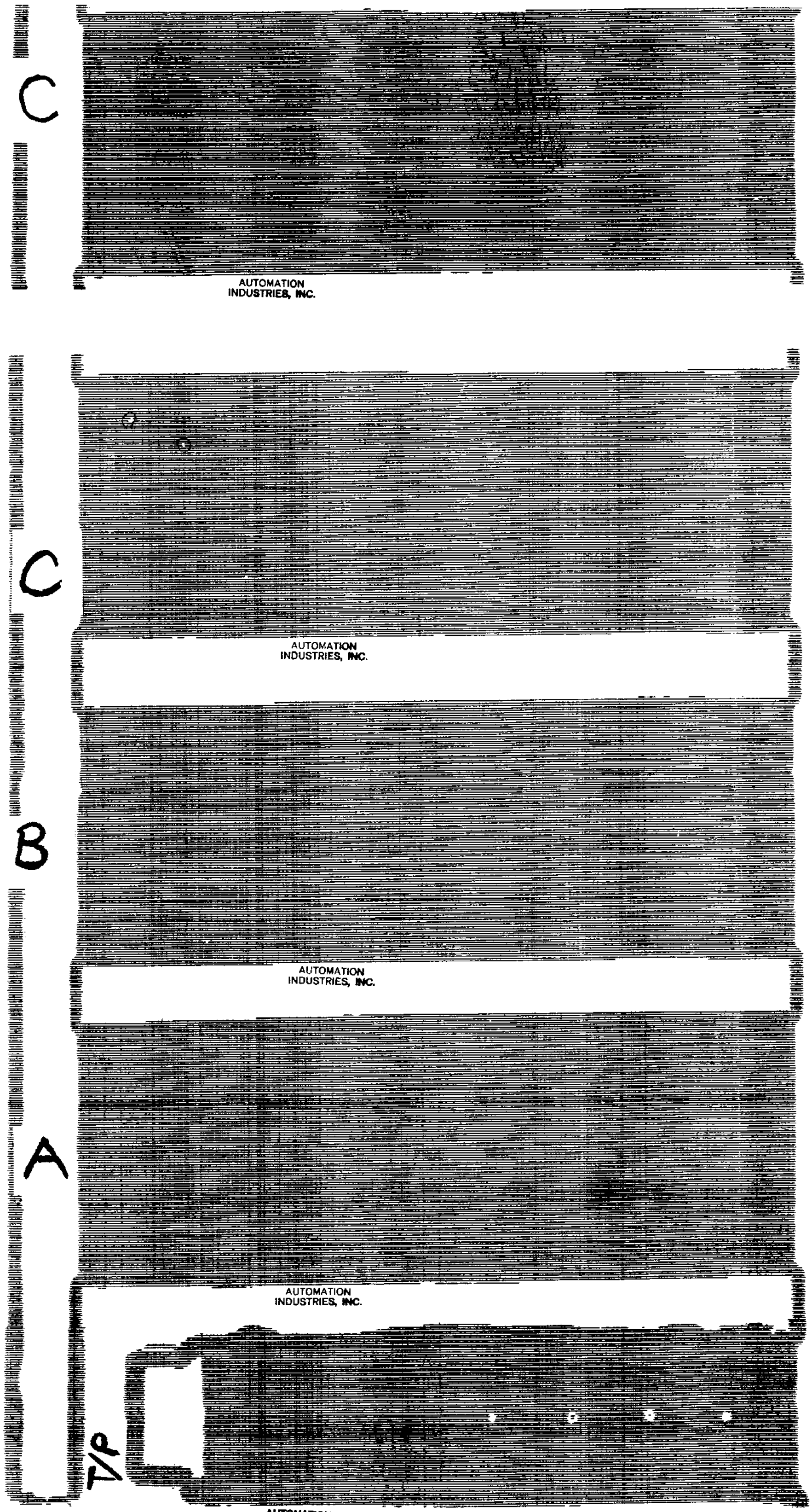


Figure 1. Autographic Plots of the Ultrasonic Longitudinal Beam Scans of Cb-1Zr Sheet to be Used for Corrosion Capsule End Caps

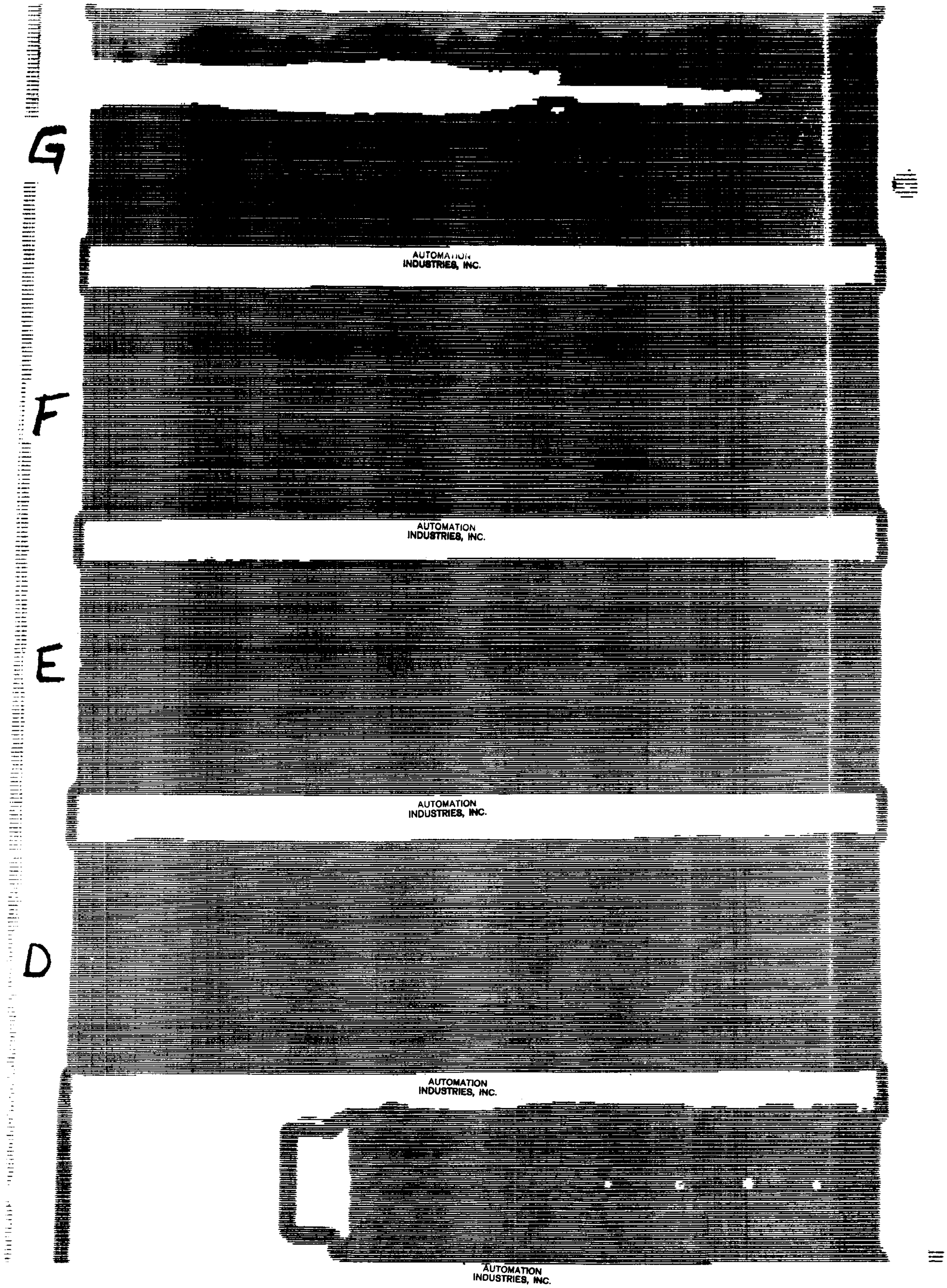


Figure 1 (Cont'd) Autographic Plots of the Ultrasonic Longitudinal Beam Scans of Cb-1Zr Sheet to be Used for Corrosion Capsule End Caps

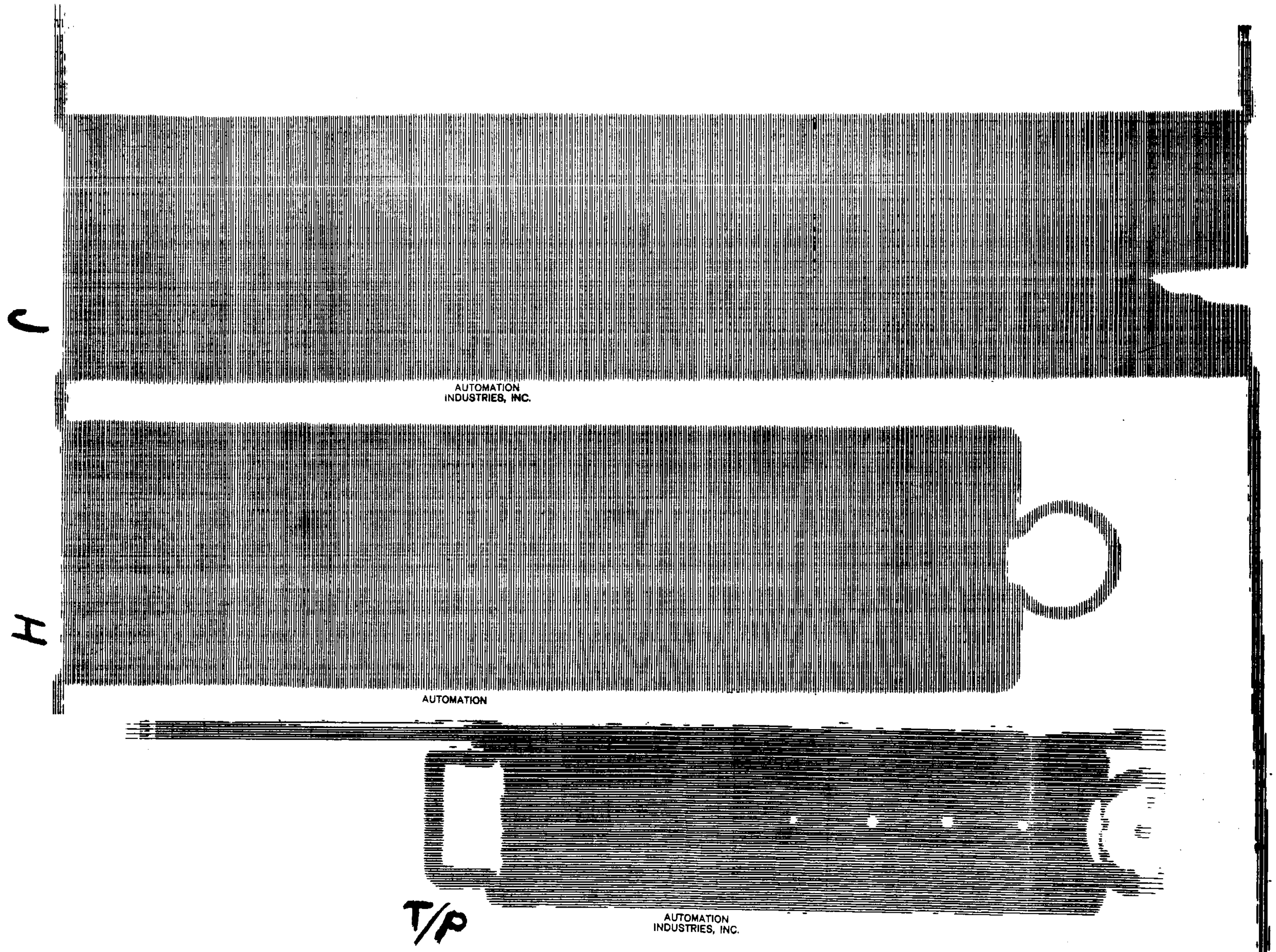


Figure 1. (Cont'd) Autographic Plots of the Ultrasonic Longitudinal Beam Scans of Cb-1Zr Sheet to be Used for Corrosion Capsule End Caps

V. TEST PROGRAM

Preliminary test plans, except for wetting and friction and wear measurements with liquid potassium and detailed test facility designs, are being prepared for each phase of the test program and will be submitted to the NASA technical manager for his review and approval the last week in July. Descriptions of the test program and any ensuing technical progress will be reported after NASA approval is received.

VI. TEST FACILITIES

Corrosion Investigation

To conduct the potassium corrosion tests, the General Electric Company has purchased a 24-inch diameter x 54-inch high bakeable vacuum chamber, Varian Associates Model VI-17. The pumping system comprises four cryogenic adsorption pumps for roughing and a 1000 ℓ/sec getter-ion pump. After the unit was received and installed, it was successfully checked out with the chamber cold, dry and empty at a vacuum of 3×10^{-10} torr, determined from the ion pump current readings, and 4.4×10^{-10} torr, read directly from a nude Bayard-Alpert ionization gauge. Figure 2 is a photograph of the system. Design of the capsule and furnace arrangement was initiated and is in progress.

Compression Testing

Drawings of the vacuum chamber which will be used for the compression testing of the selected materials have been completed and submitted to vendors for quotation. Figure 3 is a schematic drawing of the chamber. Although the chamber configuration is based on a design presently operating in the creep-rupture facility at General Electric, Evendale, modifications were necessary to accommodate the strain measuring system and the massive compression loading heads. An existent 5-inch diameter CVC, PS-40A cold trapped oil diffusion pump backed up by a CVC, 30 CFM mechanical pump will be used with the chamber.

The design of the loading train (specimen adapters, strain measuring arrangement) is nearly completed and purchase orders have been placed or are being prepared for other auxillary equipment, i.e., step-down transformers, temperature controller, platens, etc.

The facility is being purchased for the program by the General Electric Company.

Vacuum Friction and Wear Test Rig

In addition to preparing the test plans for conducting friction and wear tests in a high vacuum, considerable time has been devoted to the final design of the test apparatus. This design is based on the design of a machine in use by R. L. Johnson at NASA, Lewis Research Center. Although the design has not been formally approved by NASA, because of the advanced stage of the design work and because of the particular interest in this phase of the program, reporting the progress to date is warranted.

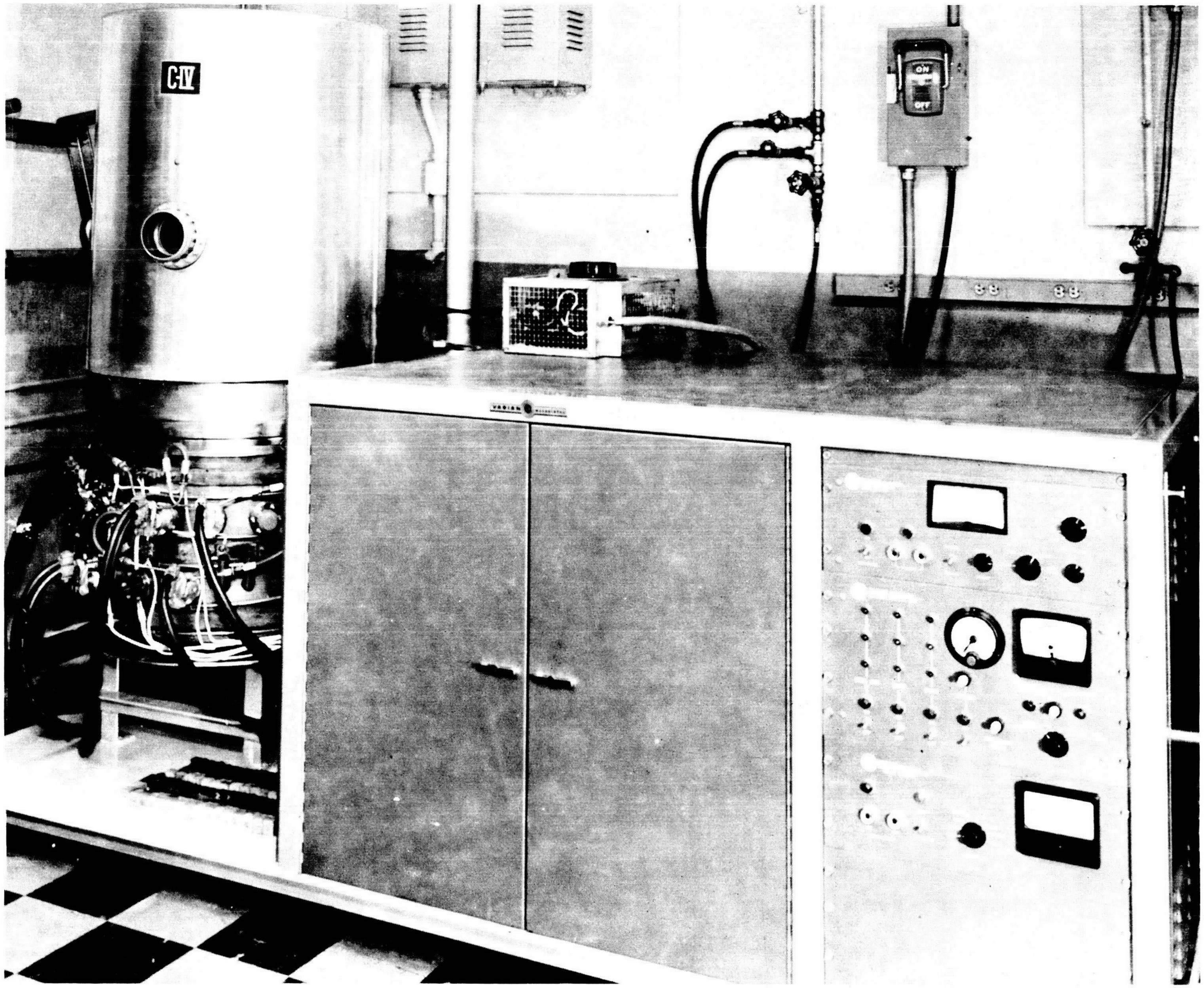


Figure 2. High-Vacuum System (10^{-10} Torr Range) to be Used in the Study of the Corrosion Behavior of Potential Potassium Lubricated Journal Bearings. The chamber is 24 Inches Diameter x 54 Inches High and Incorporates a 1000 ℓ/sec. Getter-Ion Pumping System

1. Guide, 3 - 120° apart
2. Bellows and Seal Assembly
3. Water Cooling Jacket
4. Port for Thermocouple Leads
5. Water-Cooled Electrodes
6. Vacuum Port
7. Sight Port

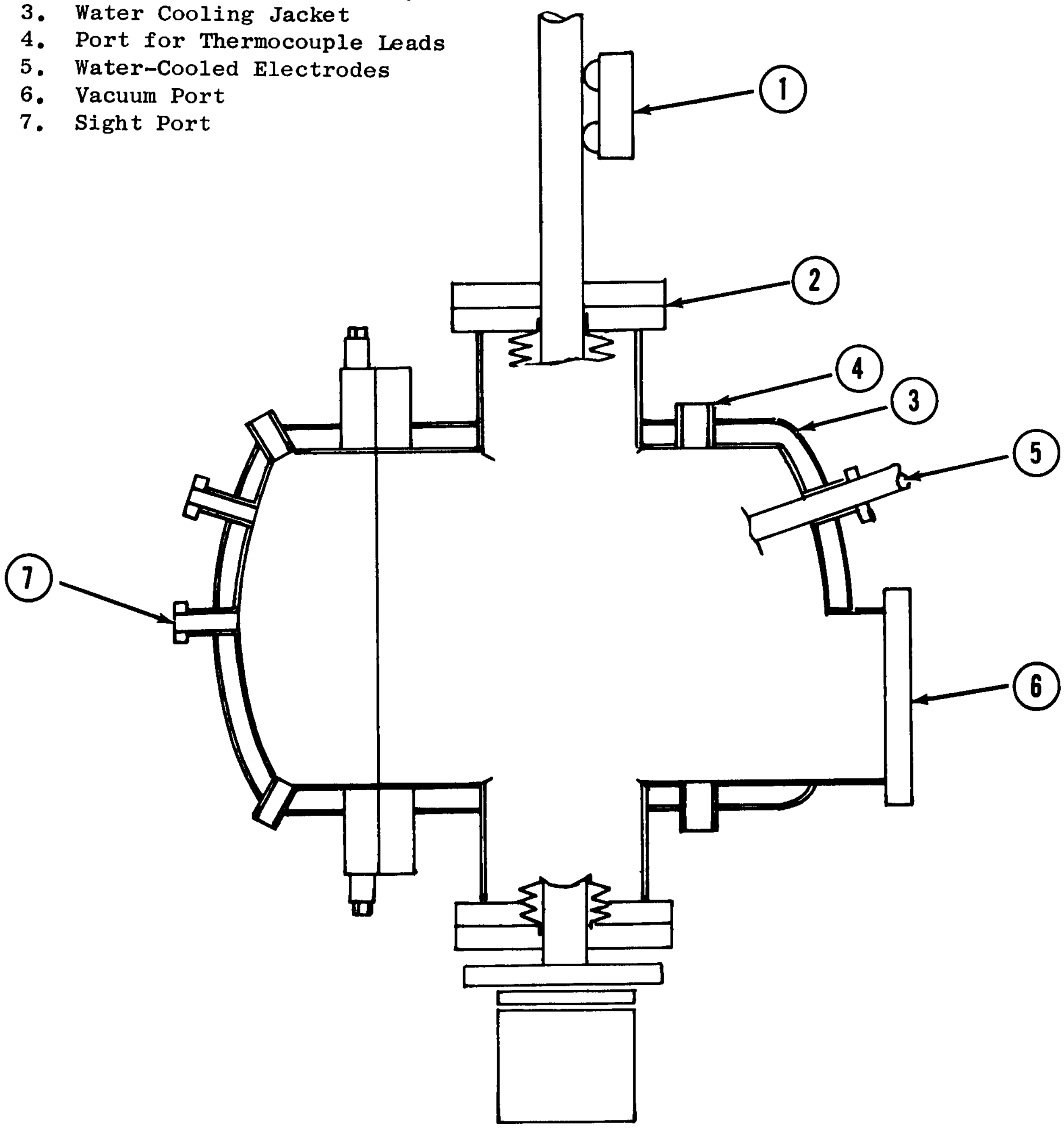


Figure 3. Vacuum Chamber to be Used for the Determination of Compressive Properties

Because of some conflicting design requirements for the high vacuum and liquid potassium tests, a decision was made initially to consider designs for two friction and wear test rigs: one, primarily for the evaluation of the selected materials in a high vacuum; the other, primarily for the evaluation of the materials when they are lubricated with liquid potassium. Currently, the design for high vacuum testing, except for detailing the test rig parts, has been completed.

Design Requirements. The dynamic test equipment to be used for the friction and wear studies has been designed to meet the following requirements:

1) The test section must be completely sealed and capable of operating in a vacuum of 10^{-9} torr. Consequently, all mechanical parts inside the vacuum chamber must be designed as simply as possible to minimize outgassing.

2) The spindle bearings must be replaceable. All test specimens must be replaced as simply as possible.

3) The test specimens must be evaluated under the following conditions: temperature, $1600^{o}F$ maximum; speed, 5000 sfm maximum; load, to 0.2% of the yield stress (hertzian).

4) Readout of data must be accurate.

Vacuum System. The high vacuum system for the vacuum friction and wear tests also was purchased for the program by the General Electric Company from General Electric's Vacuum Products Department, Schenectady, New York. The unit, shown in Figure 4, consists of an 18-inch diameter x 30-inch high bakeable chamber in conjunction with three cryogenic adsorption pumps for roughing and a 1000ℓ/sec getter-ion pump. During the reporting period, the system was received, installed and is now undergoing checkout tests with the chamber cold, dry and empty. In the first checkout test, the system was opened, resealed, baked out, and evacuated to a pressure of approximately 1×10^{-9} torr in a 24-hour period.

Test Rig Design. The over-all layout of the friction and wear test equipment is shown in Figure 5. Basically, this rig consists of a vacuum chamber which houses a ball bearing mounted spindle. The vacuum chamber is fitted directly on the flanges of the high vacuum pumping system described in the preceding paragraph. The ball bearing mounted spindle has a relatively long overhang with two detachable discs mounted at the bottom. Two ring-shaped test specimens are attached to each disc. The top end of the spindle supports one

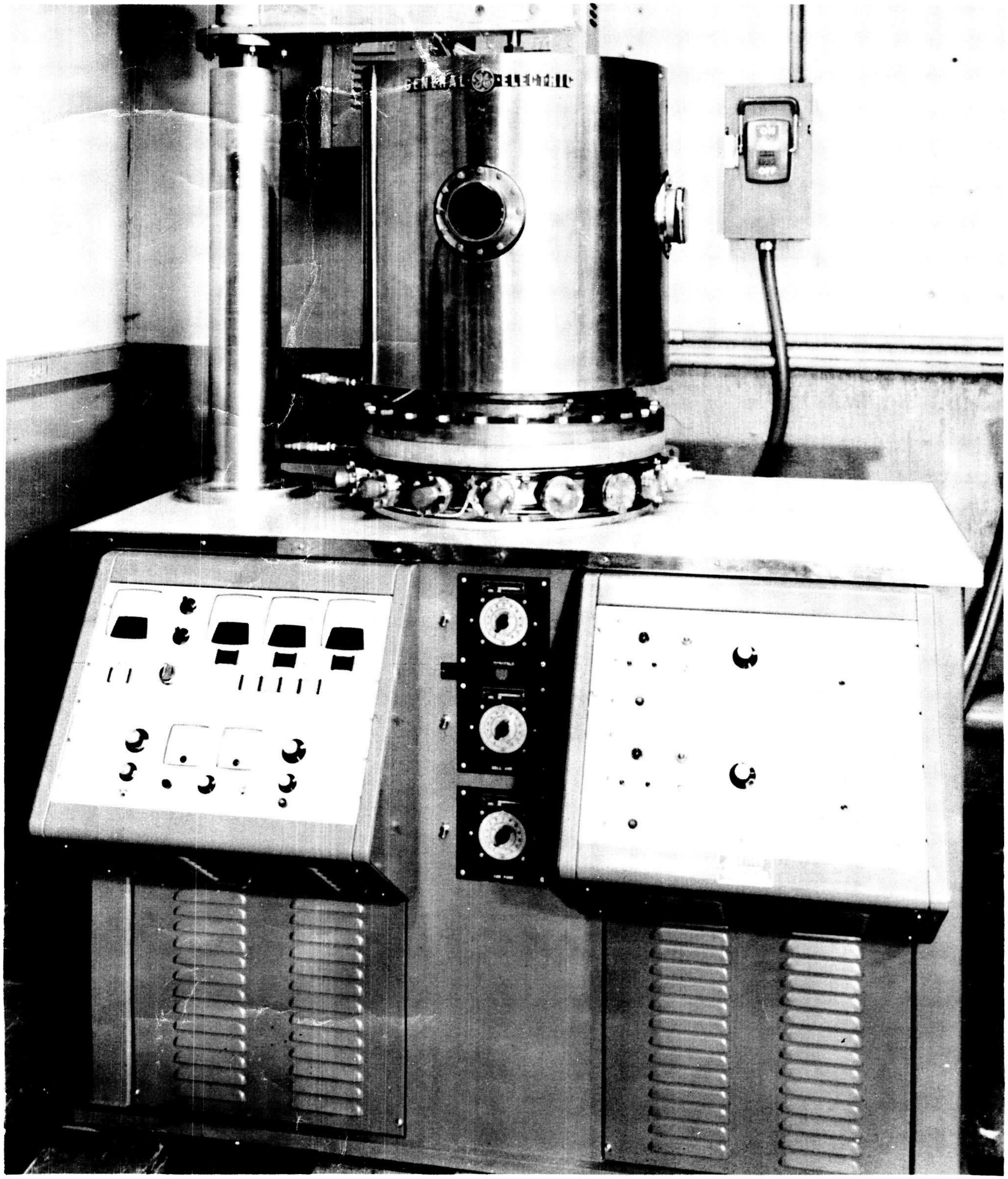
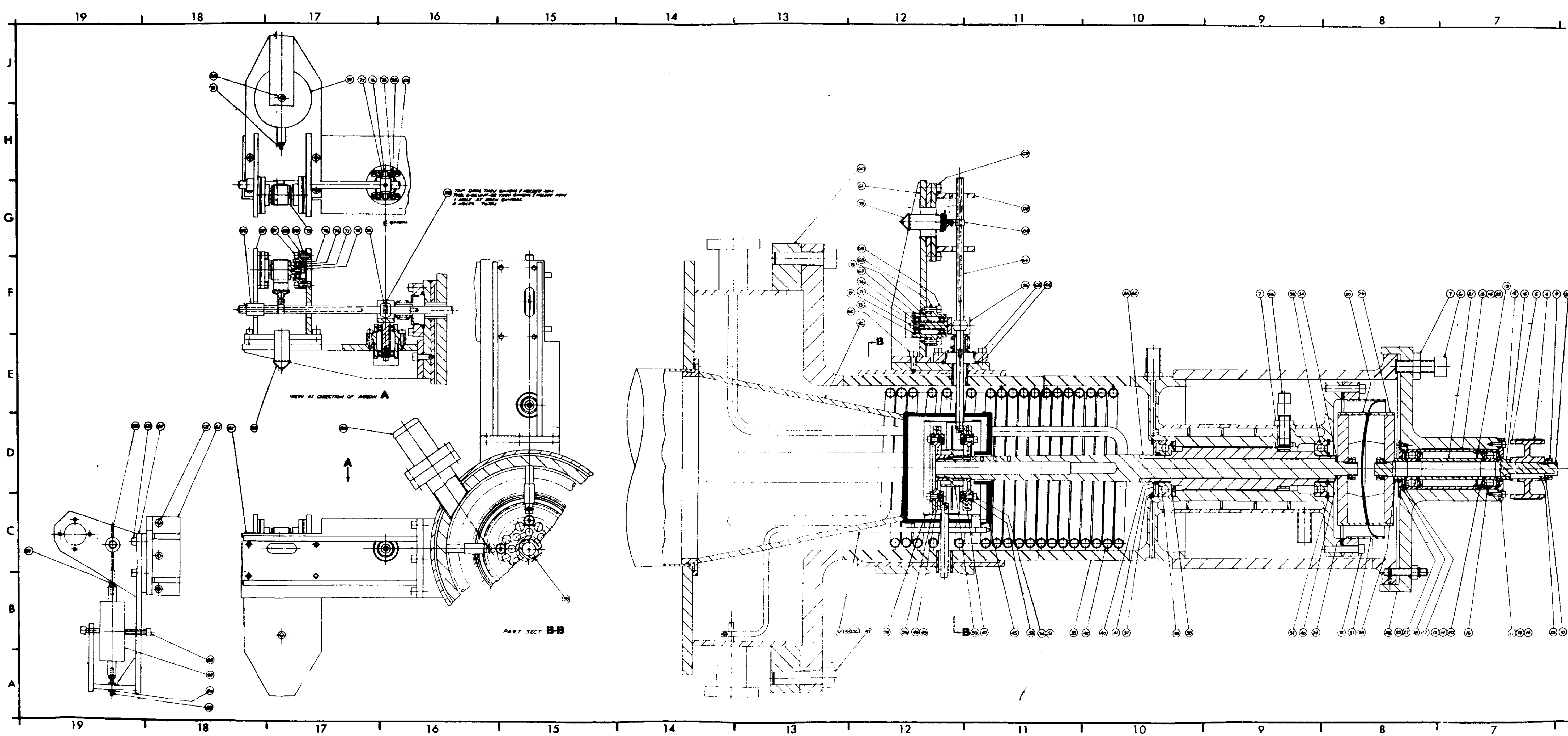


Figure 4. High-Vacuum System (10^{-10} Torr Range) to be Used in the Study of Friction and Wear of Potential Potassium Lubricated Journal Bearings. The Chamber is 18 Inches Diameter x 30 Inches High and Incorporates a 1000 ℓ/sec. Getter-Ion Pumping System



VIEW IN DIRECTION OF ARROW A
PART SECT B-B

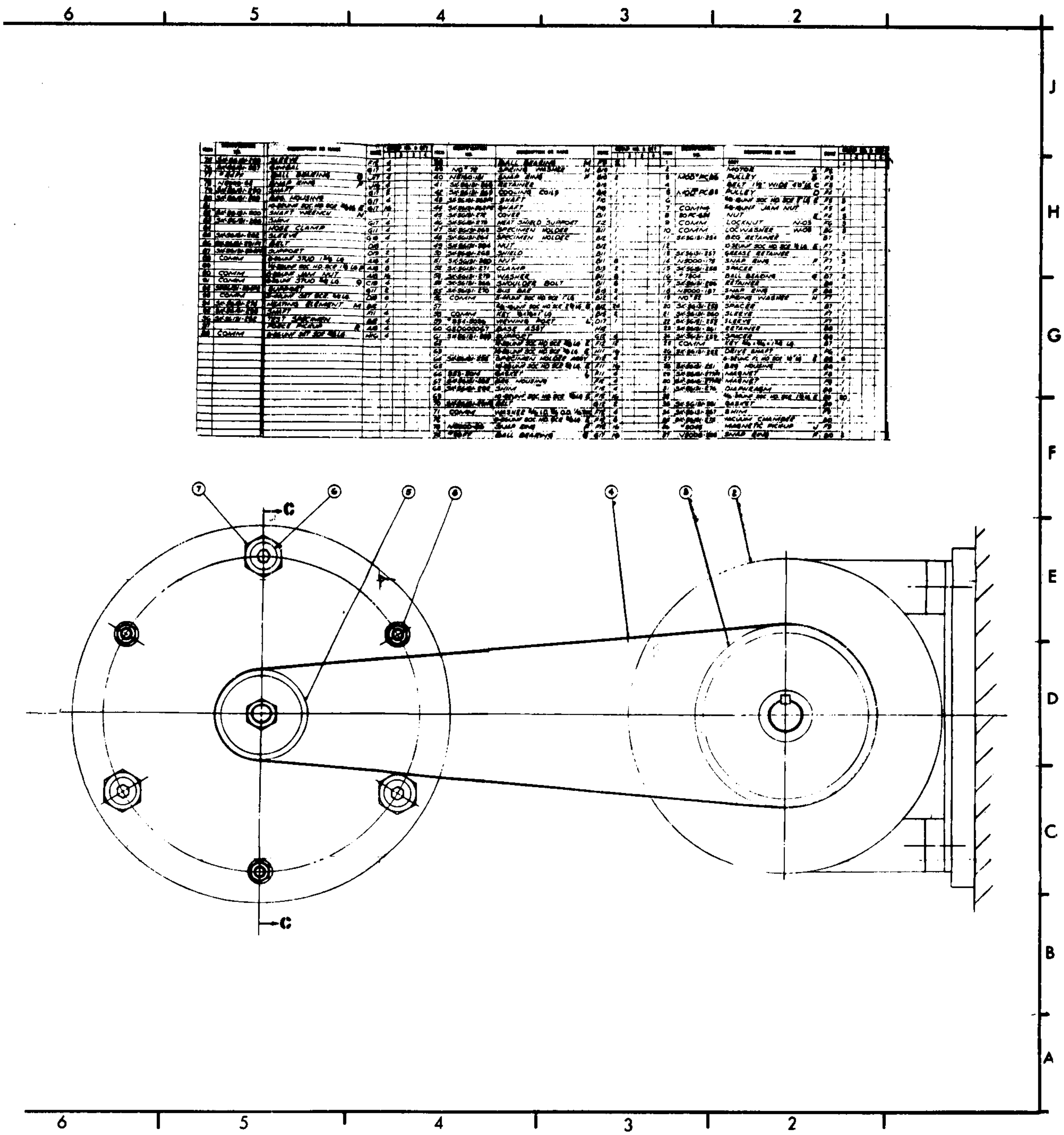


Figure 5. High Vacuum Friction and Wear Tester Assembly Drawing

Alnico V magnet of a synchronous, permanent magnet clutch. The torque of the magnetic clutch is transmitted through a thin, 0.032-inch Inconel membrane which hermetically seals the vacuum chamber. The outside magnet of the clutch, located at the top of the vacuum chamber, is attached to a grease-lubricated ball bearing mounted spindle that is belt-driven by a 5 hp stepless variable speed thymotrol motor. The speed of the test spindle will be variable between 100 and 5000 rpm.

Heating the friction and wear test specimens is accomplished by radiation from a tantalum resistance heater surrounding the test specimens. The four stationary rider specimens, mounted in Rene' 41 alloy loading arms, penetrate the vacuum chamber wall; each arm is offset 90°. Flexible bellow seals are fusion welded to the individual arms and the detachable copper-gasket vacuum flanges. Using this sealing technique, the load arms extend into the atmosphere where they are mounted in a gimbal arrangement so that they can move as freely as required by the load application and torque measurement systems. The frictional torques are measured with sensitive strain gauges and the loads are applied by gravity weights.

Rotor and Bearings. The quality of the test apparatus is determined predominantly by the design rotor, which carries the test specimens, and the proper arrangement of its bearings. Various factors influence the rotor design:

1) Rotating test specimens must be heated to 1600°F and the bearings should operate at the lowest possible temperatures.

2) The rotor carrying the test specimen must run smoothly and with the minimum vibrations to assure high quality of friction and wear test data.

3) The high vacuum environment imposes problems in selecting bearings capable of operating successfully under the test conditions for sufficiently long times. Regardless of the bearing type, the high surface speed (5000 fpm) of the test specimens favors small bearing diameters.

4) The questionable life expectancy of even the most suitable bearing type for high vacuum operation demands that the rotor and bearings can be removed easily and the bearings replaced.

5) Bearings loads must be minimized.

6) Rotor drives in hermetically sealed vacuum chambers are power limited.

The divergency of these factors requires compromises. First, an attempt was made to reduce the spindle speed to the lowest possible value without impairing simplicity, power consumption of the test spindle and over-all size of the test rig. As Figure 6 indicates, spindle speed drops sharply if the wear diameter of the test specimen is increased. A 4-inch wear diameter of the test specimen is tolerable with respect to the required spindle torque and over-all test rig dimension.

Simplicity in design favored mounting the test specimen on an overhung shaft. To obtain a smooth running spindle, it is desirable to minimize the spindle overhang. However, to minimize thermal loading of the bearings, which is caused by heat flow from the hot test specimen section (1600°F) along the rotating shaft, the spindle overhang has to be appreciably long. Considerable effort was expended on an acceptable compromise between bearing spacing, spindle overhang, critical shaft speed and thermal loading of the bearings. Unfortunately, the existing computer program for determining the temperature distribution in components like the shaft could not be employed because the main mode of heat transfer in this case is radiation.

The complexity of heat transfer by radiation permitted only a parametric study of the temperature distribution along the shaft, which had to be performed in parallel with studies of the spindle's vibrational characteristics. In this analysis, the shaft was considered a fin transferring heat by radiation into an enclosure with uniform temperature. The following assumptions were made:

1) The emissions and reflections from all surfaces are diffuse, i.e., Lambert's cosine law is obeyed.

2) The view factors from a differential area on the fin surface to the enclosing surfaces are essentially constant over the fin surface.

3) Emissivity is not a function of temperature.

4) Shaft material is M-252 alloy.

To a large extent, the analysis utilized work reported by Lieblein.[138] The following equations, together with Figure 7, have been used to determine the shaft temperature at the location of the lower bearing:

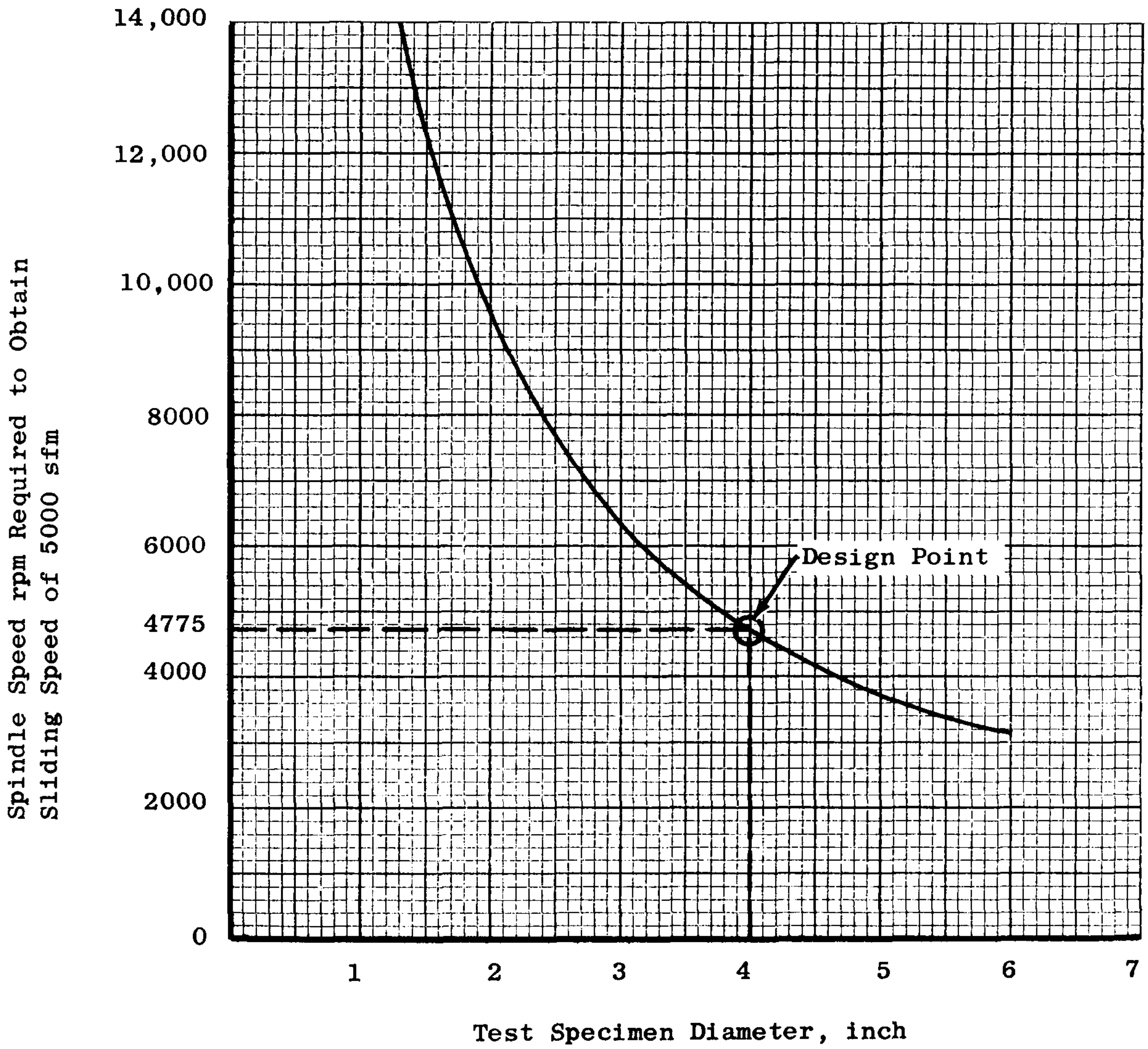


Figure 6. Effect of Test Specimen Diameter on the Spindle Speed Required to Obtain a Surface Speed of 5000 sfm

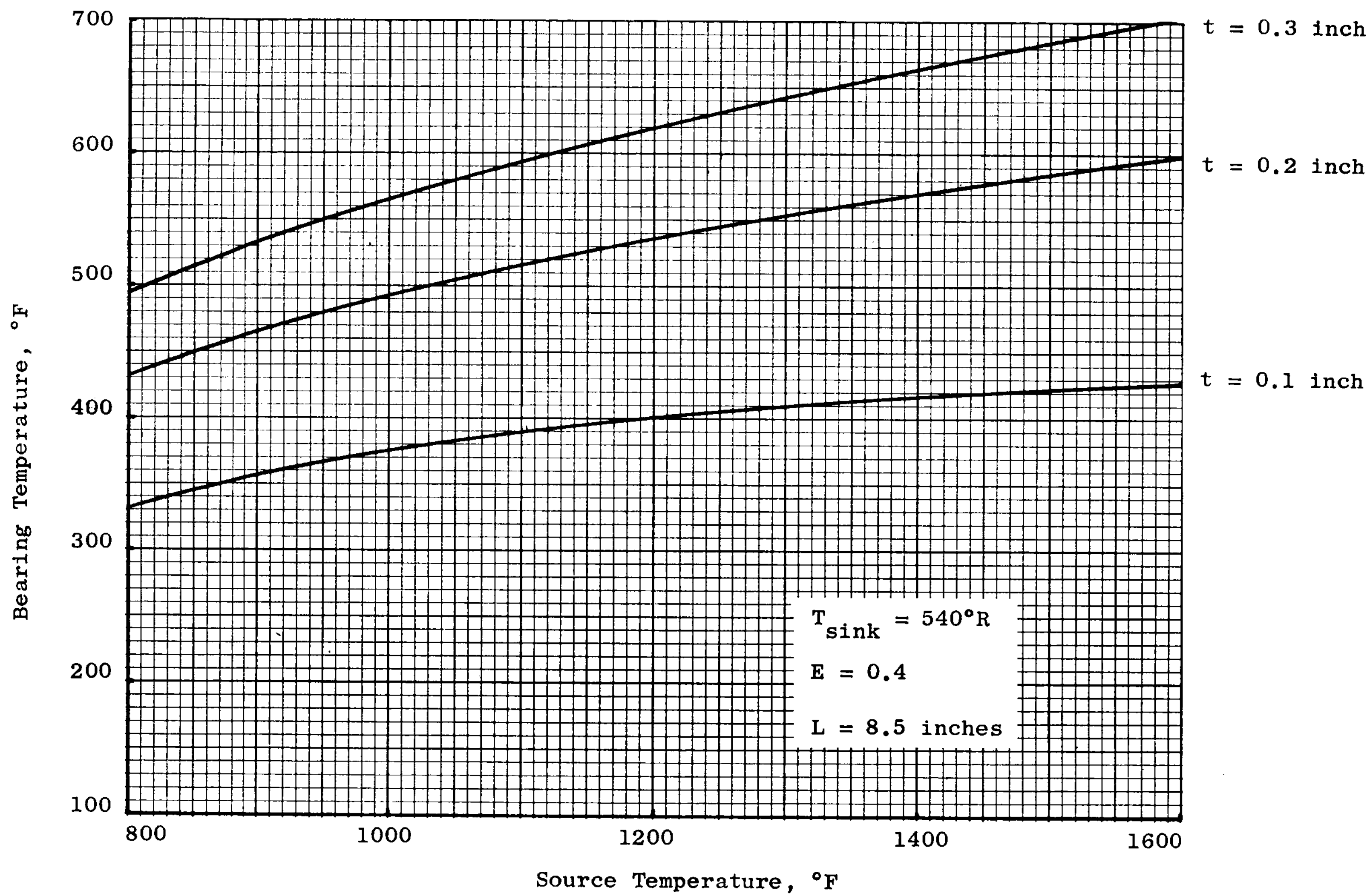


Figure 7a. Spindle Bearing Temperature as a Function of the Test Temperature, Emissivity and Spindle Thickness

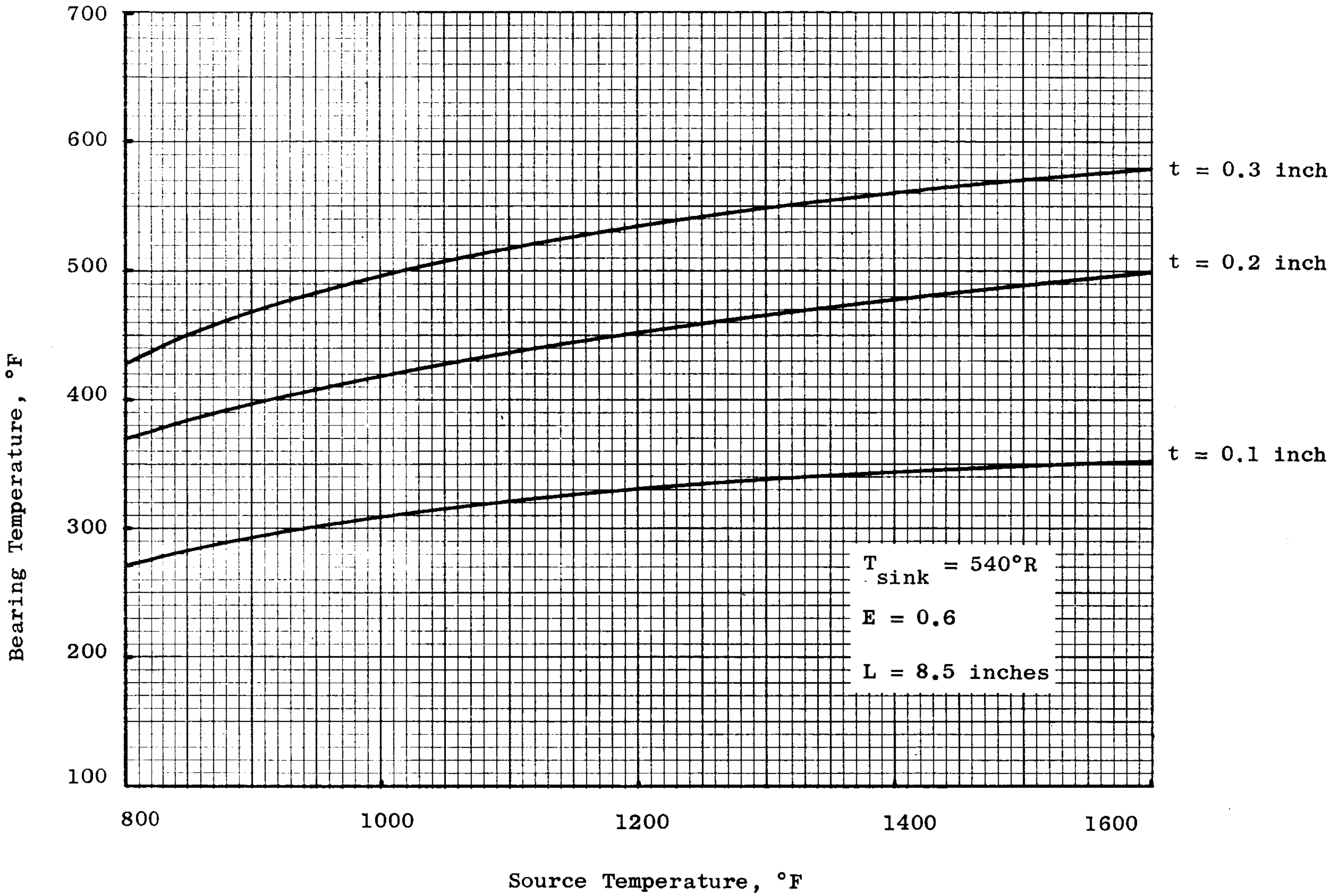


Figure 7b. Spindle Bearing Temperature as a Function of the Test Temperature, Emissivity and Spindle Thickness

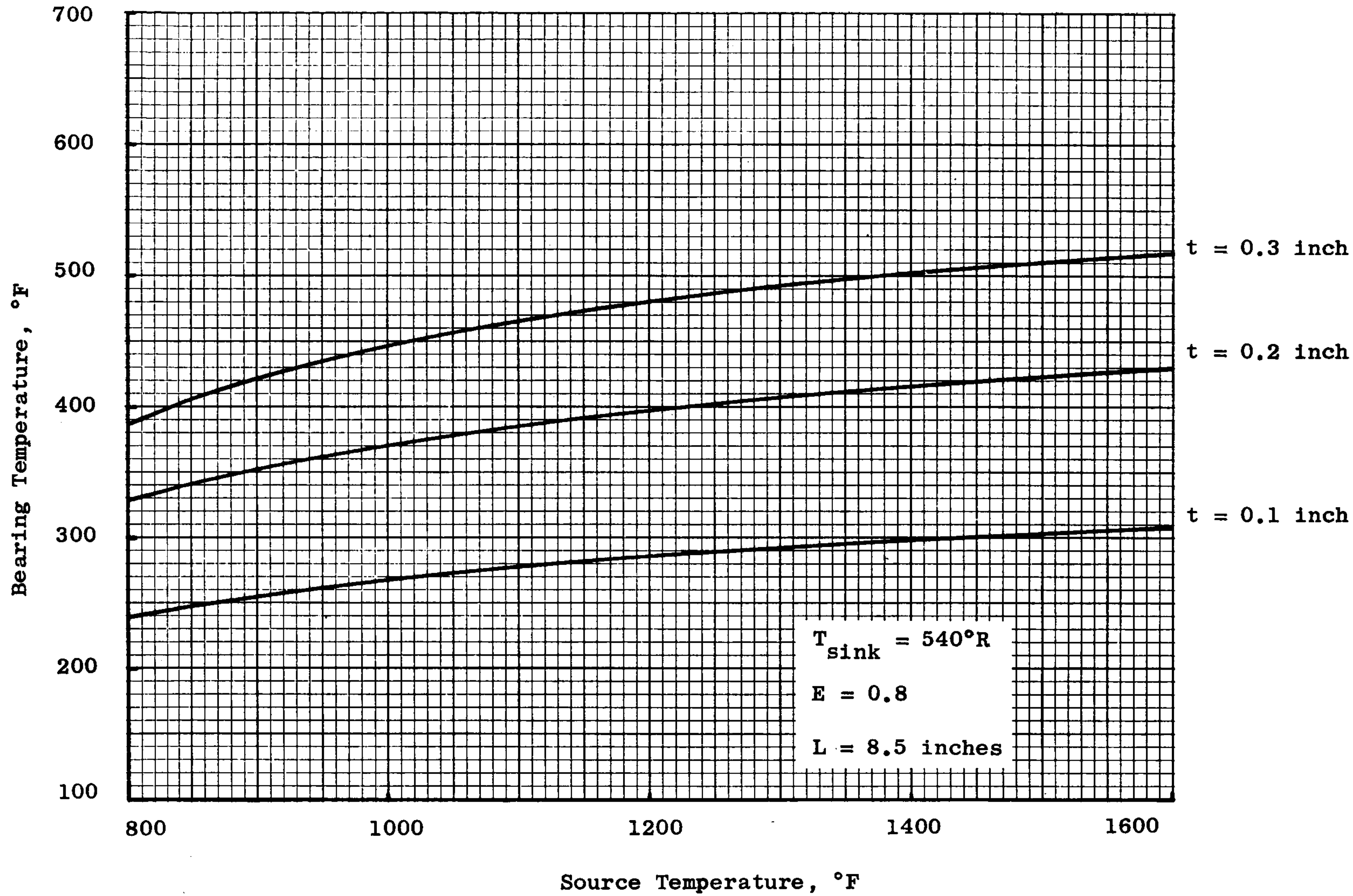


Figure 7c. Spindle Bearing Temperature as a Function of the Test Temperature, Emissivity and Spindle Thickness

$$L = \ell \sqrt{\frac{\sigma \varepsilon}{k\ t} T_o^3} \qquad (1)$$

$$E = \frac{1}{\frac{1}{\varepsilon} + \left(\frac{1}{\varepsilon_s} - 1\right)\frac{A}{As}} \qquad (2)$$

where L = generalized length parameter

ℓ = fin length (shaft length)

E = emissivity view factor

k = thermal conductivity of shaft material

t = thickness of fin

T_o = source temperature

ε = fin emissivity

ε_s = sink emissivity

A = fin area

As = sink area

σ = Boltzman's Constant, $.173 \times 10^{-8}$ (Btu/hr)$ft^2.R^4$

R = Rankine temperature

Figures 7 through 10 summarize the results. Figures 7(a) through 7(c) illustrate bearing test temperature for various emissivity view factors, E, and fin thicknesses, t (t = 2x actual shaft wall thickness), as a function of the test specimen temperature (source temperature) for a constant length overhang (L = 8.5 inches). The sink temperature in this case is 540°R; enclosure walls are water-cooled. Figures 8(a) through 8(c) show the same relationships for a lower sink temperature; enclosure walls are cooled with liquid nitrogen. The effect of a lower sink temperature upon bearing heat temperature apparently is minimal. The shaft thickness, however, has a significant effect on the bearing temperature.

From Figures 9(a) through 9(c) and 10(a) through 10(c), the length of the overhang necessary to maintain a selected temperature, T_L, of the exposed bearing can be determined. The plot is a function of the test specimen temperature (source temperature) for various

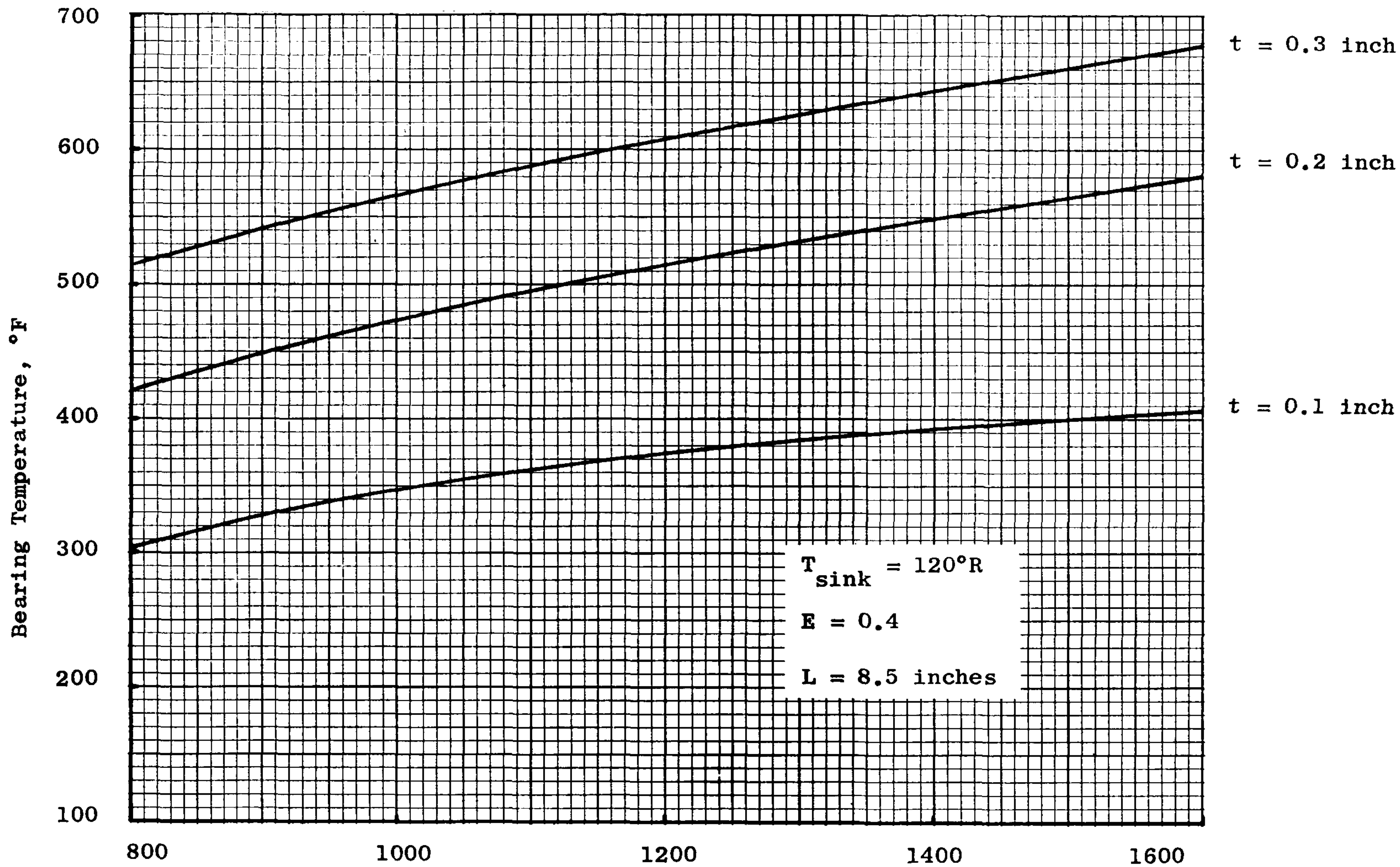


Figure 8a. Spindle Bearing Temperature as a Function of the Test Temperature, Emissivity and Spindle Thickness

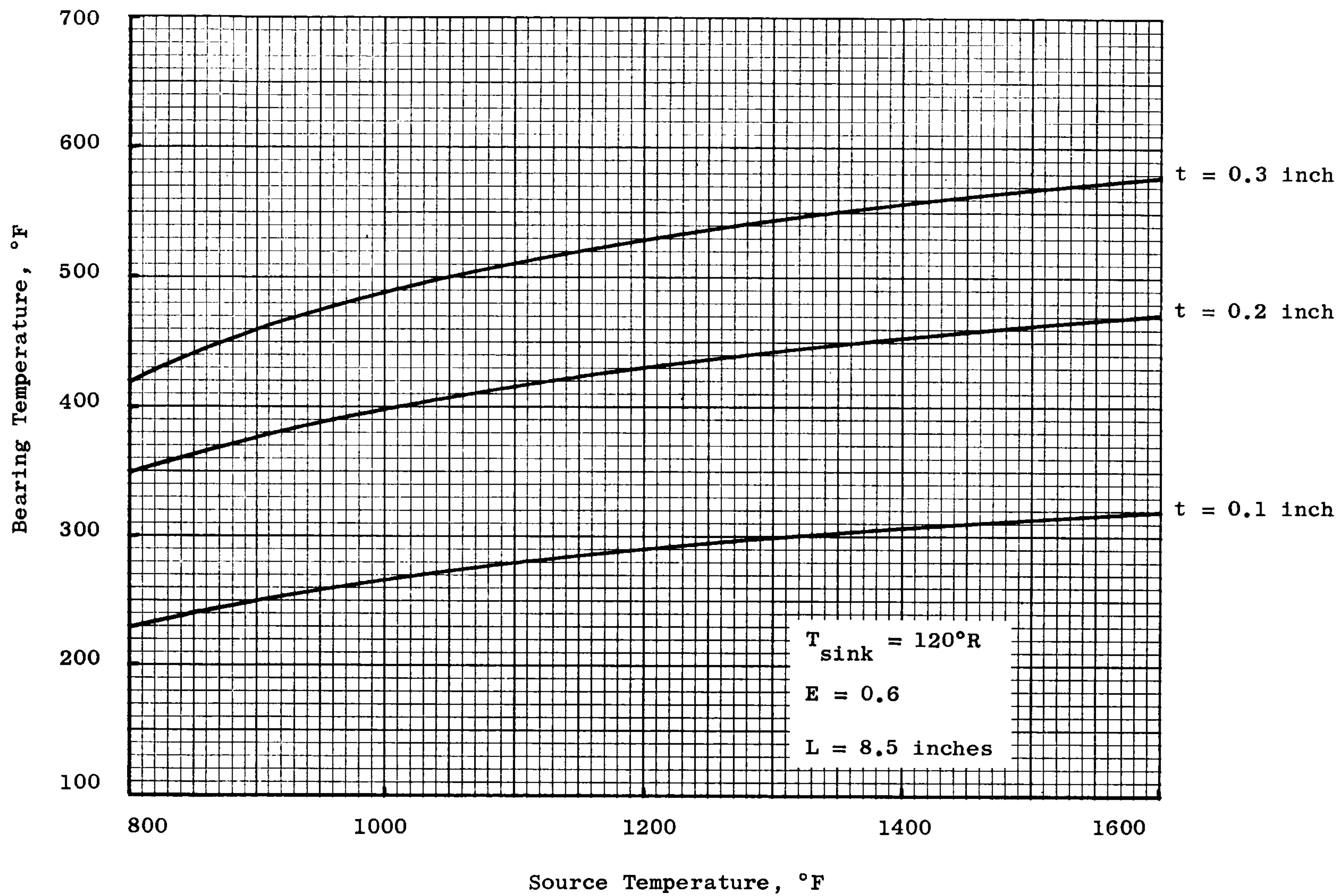


Figure 8b. Spindle Bearing Temperature as a Function of the Test Temperature, Emissivity and Spindle Thickness

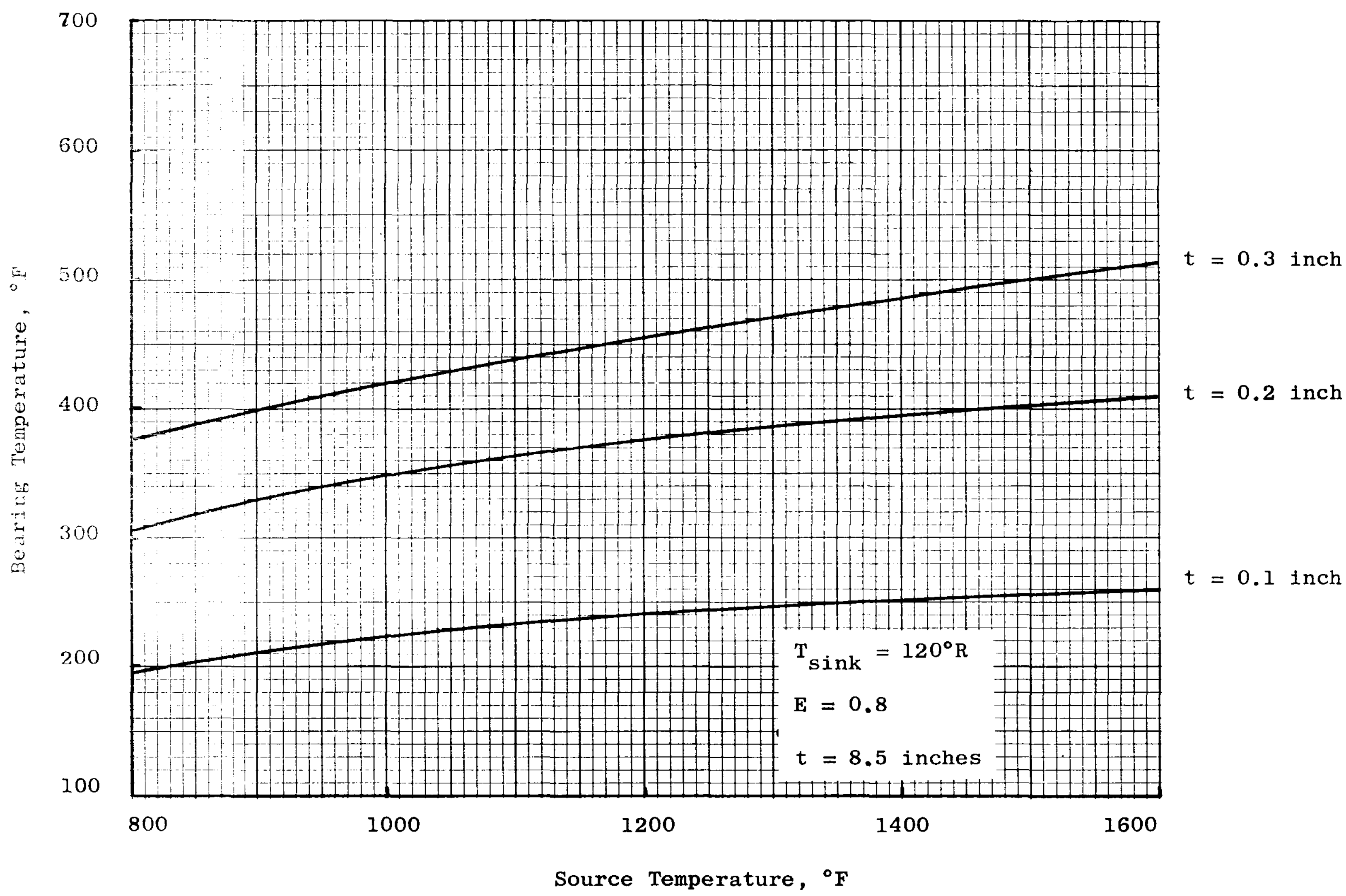


Figure 8c. Spindle Bearing Temperature as a Function of the Test Temperature, Emissivity and Spindle Thickness

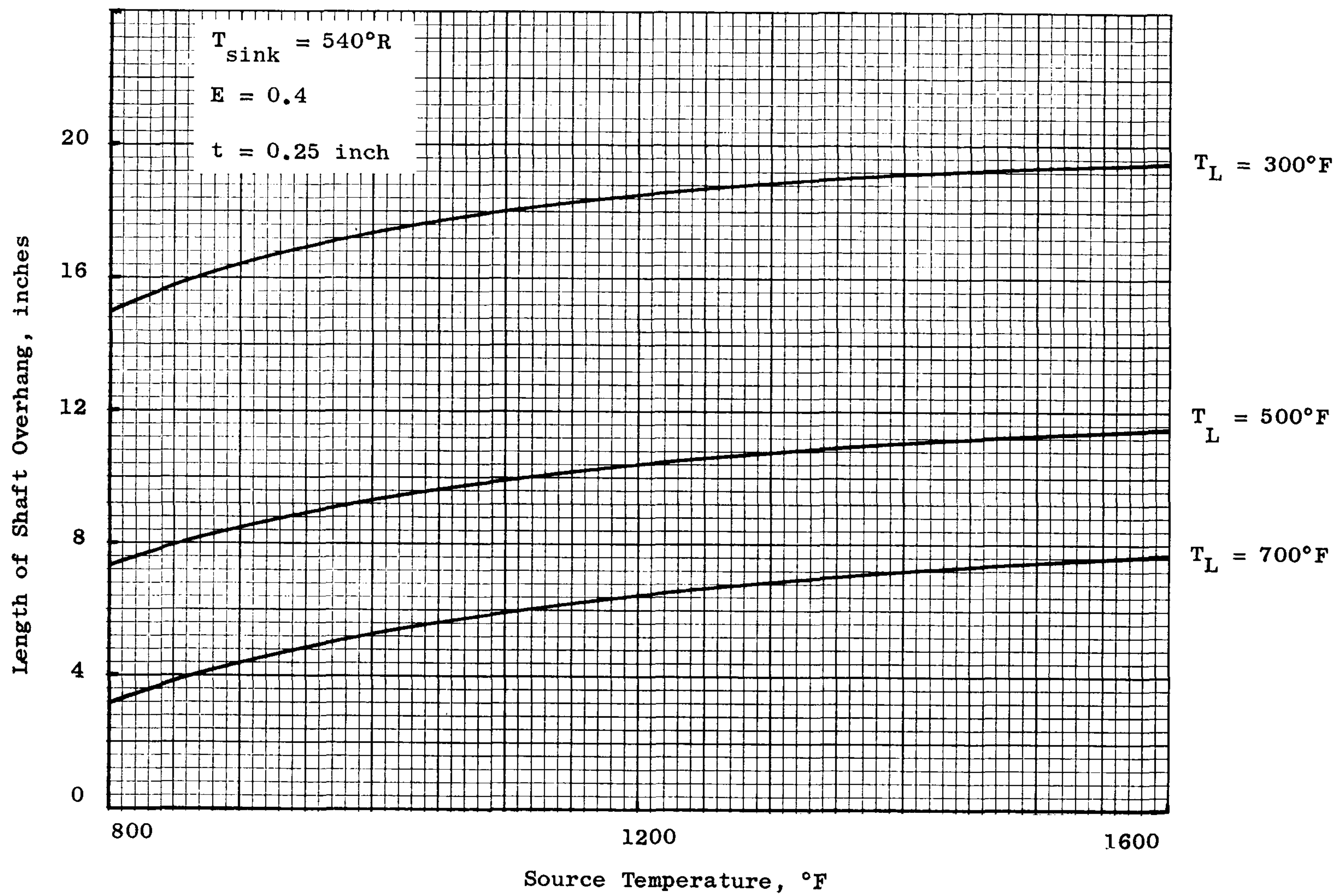


Figure 9a. Spindle Bearing Temperature as a Function of Length of Shaft Overhang, Emissivity and Test Temperature

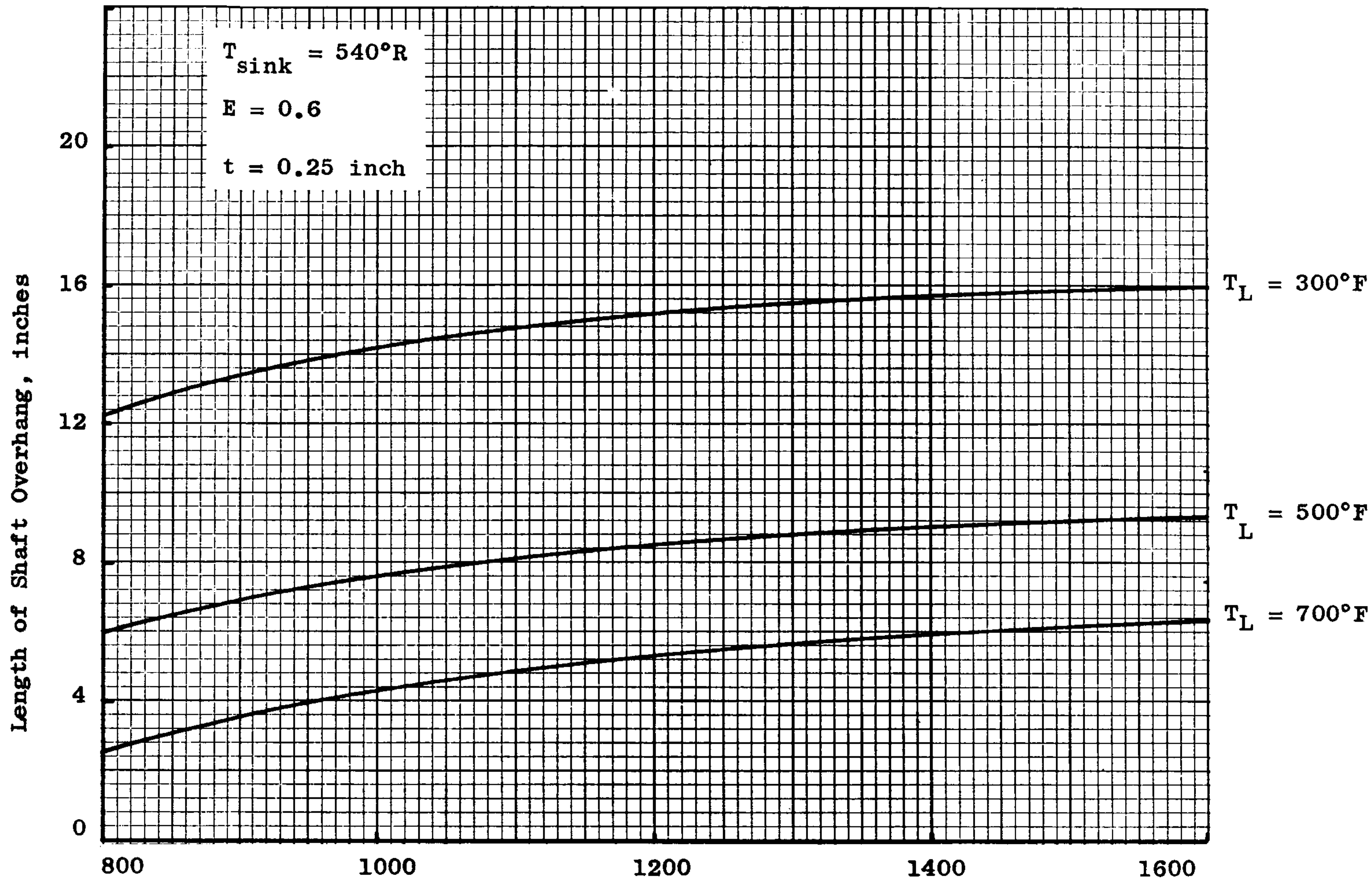


Figure 9b. Spindle Bearing Temperature as a Function of Length of Shaft Overhang, Emissivity and Test Temperature

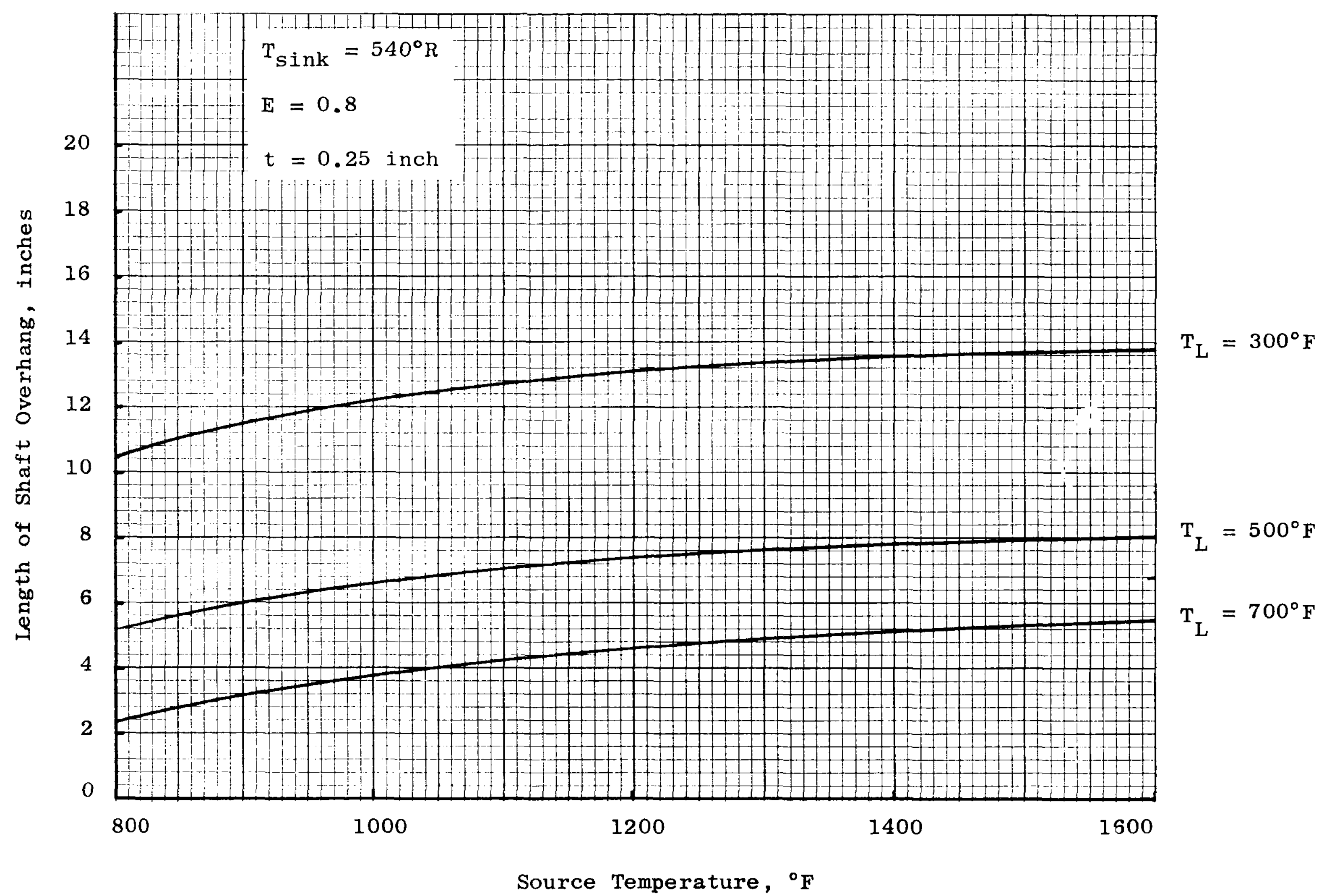


Figure 9c. Spindle Bearing Temperature as a Function of Length of Shaft Overhang, Emissivity and Test Temperature

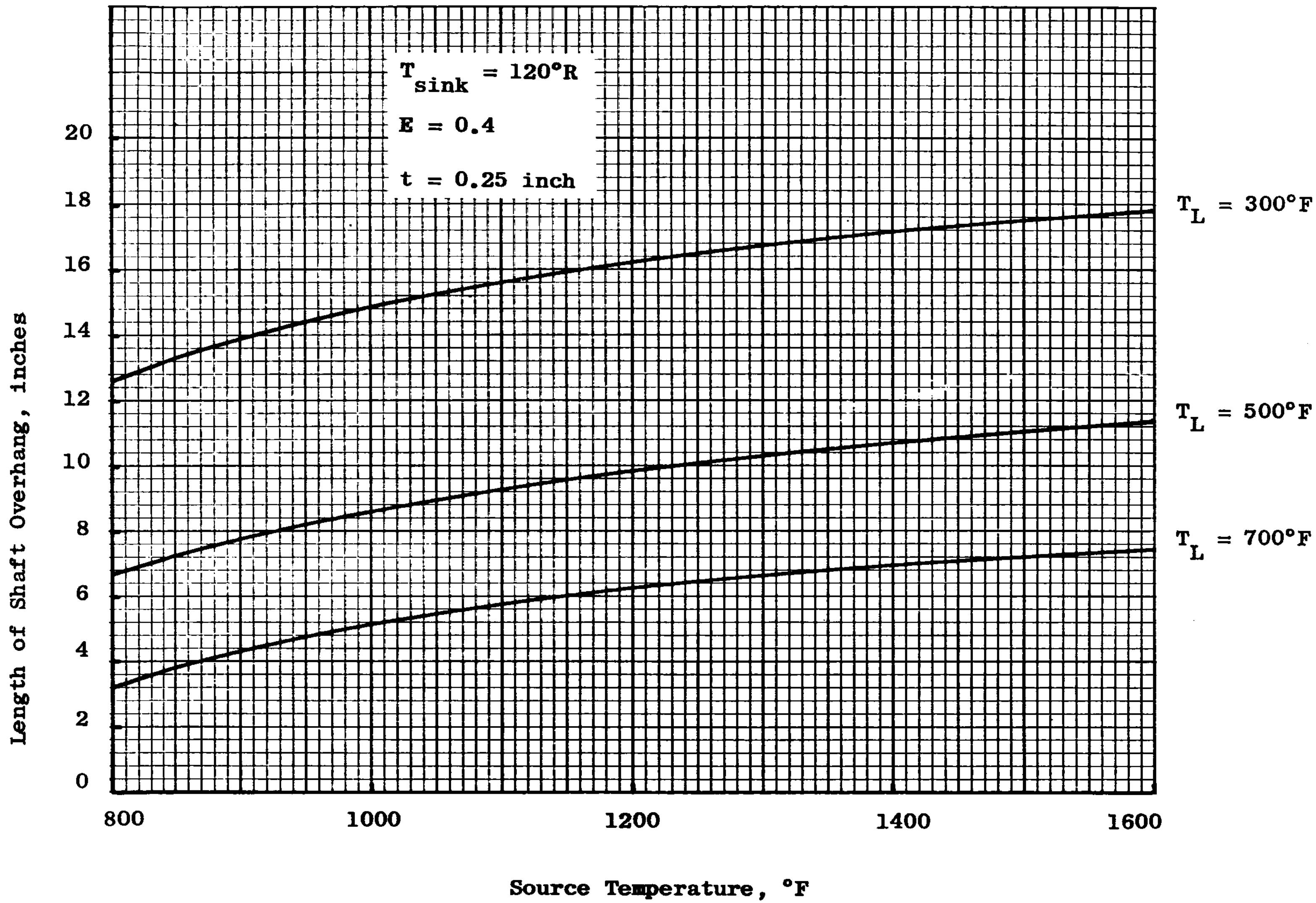


Figure 10a. **Spindle Bearing Temperature as a Function of Length of Shaft Overhang, Emissivity and Test Temperature**

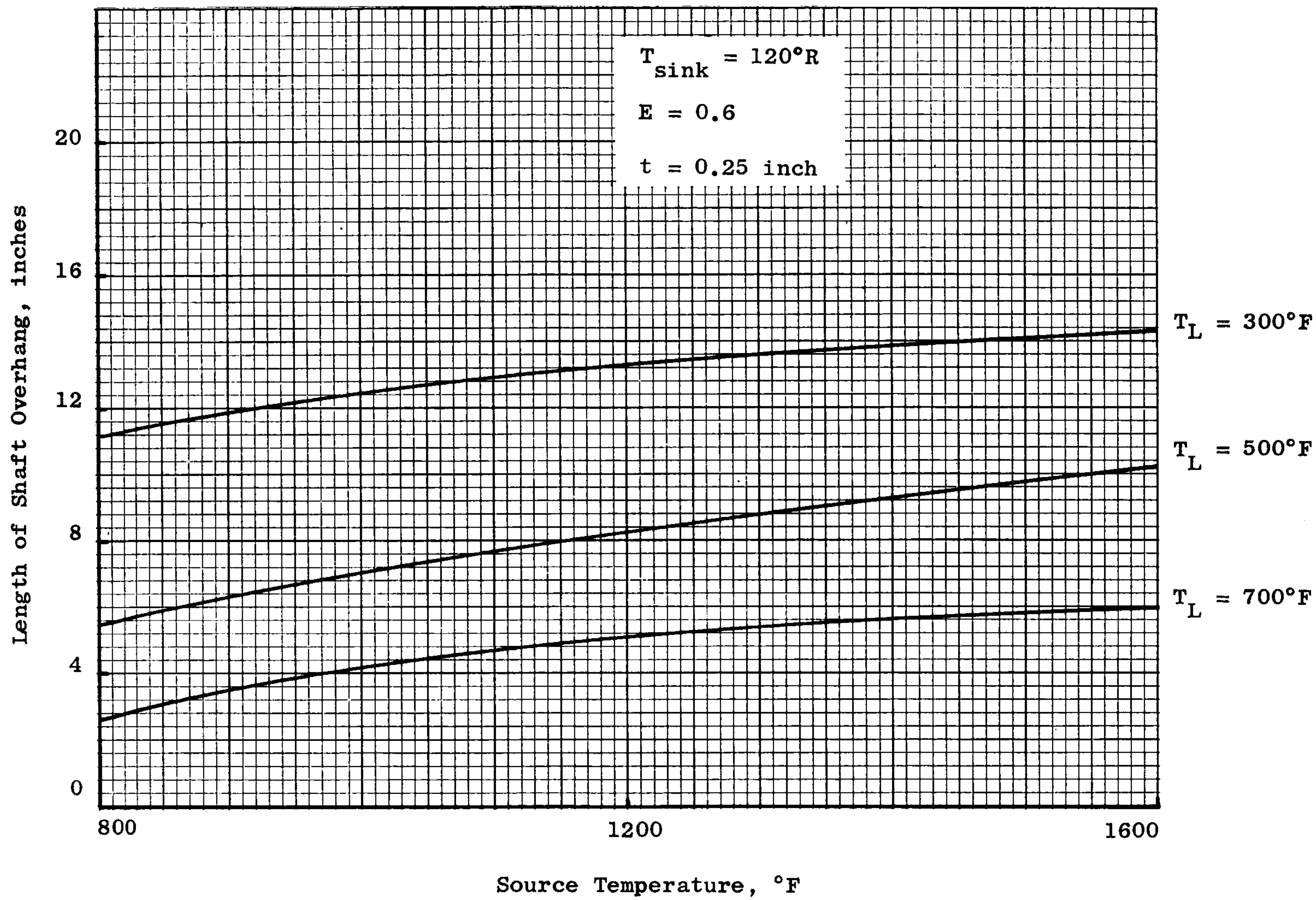


Figure 10b. Spindle Bearing Temperature as a Function of Length of Shaft Overhang, Emissivity and Test Temperature

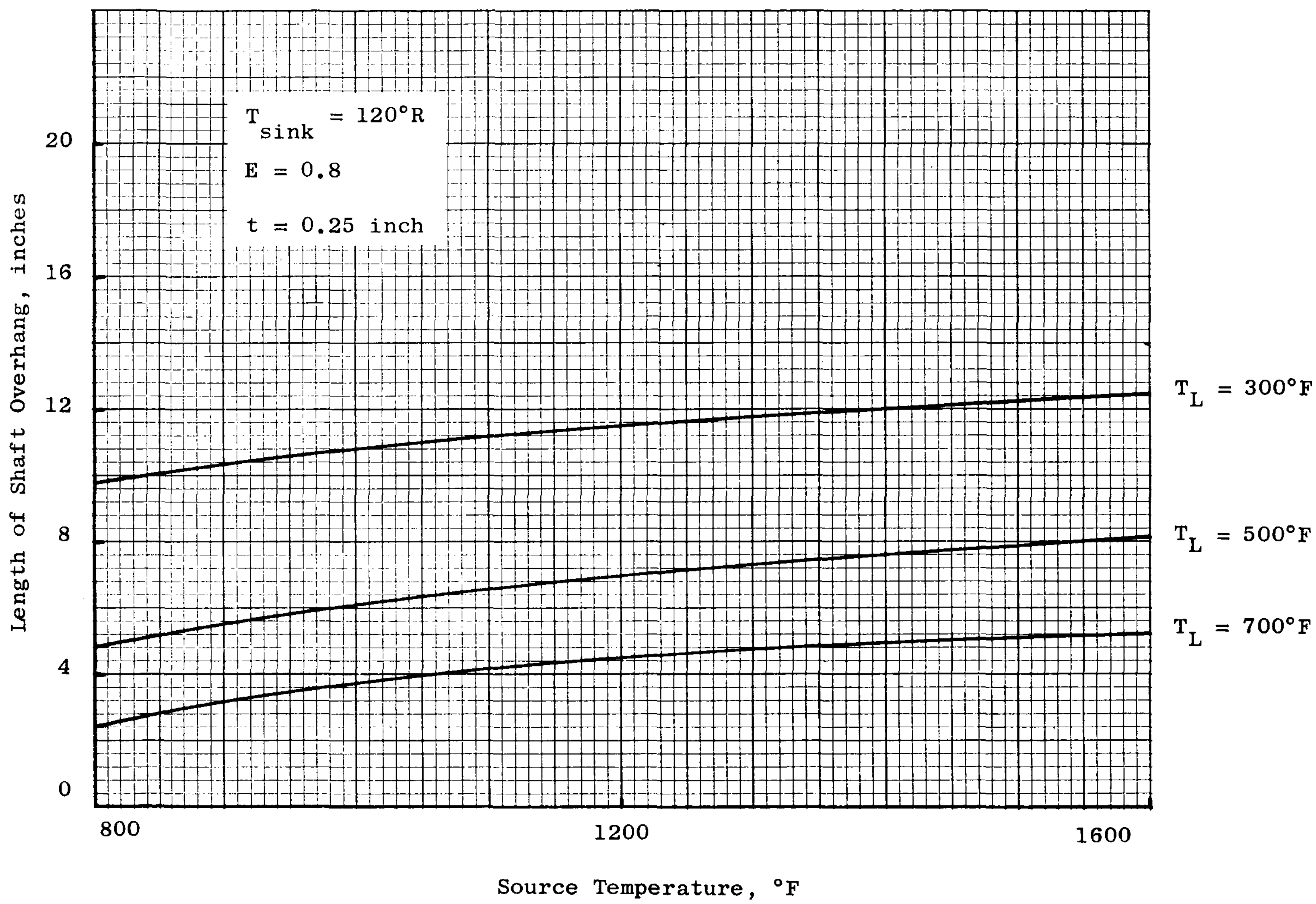


Figure 10c. Spindle Bearing Temperature as a Function of Length of Shaft Overhang, Emissivity and Test Temperature

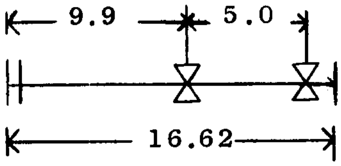
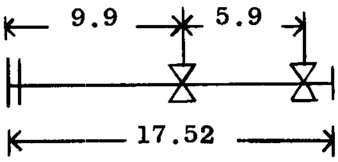
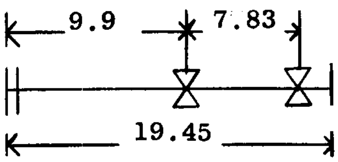
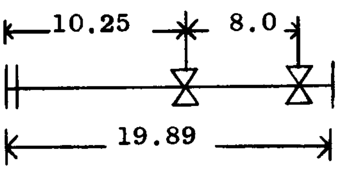
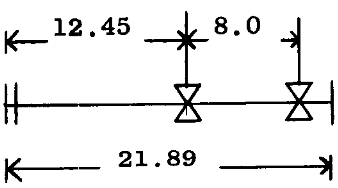
emissivity view factors, E, and a constant shaft wall thickness. Except for the sink temperature, these figures are identical. Here, again, the effect of low sink temperatures is small. In addition to the advantages of radiative heat transfer, cooling the enclosure with liquid nitrogen has another beneficial effect in this particular application; it will provide significant cryogenic pumping capacity. For this reason, liquid nitrogen will be used in the cooling coils that surround the test section and the overhung shaft. The shaft material selection also affects the heat transfer in that the candidate material should have not only appropriate strength and rigidity at the elevated temperatures but also low thermal conductivity. For these reasons, M-252 has been selected for the shaft material.

As Figures 9 and 10 indicate, considerable overhang of the shaft is required to maintain low shaft temperatures near the exposed bearing. Because of the nature of radiative heat transfer, removing heat by radiation becomes increasingly difficult as the shaft temperature approaches the sink temperature. Therefore, additional means have been provided to minimize conductive heat flow along the shaft into the bearing area. The shaft tapers from the hot test section toward the bearing, and holes have been drilled in the least stressed portions of shaft and in the support discs of the test specimen that are attached to the shaft. The conductive heat flow into the bearing is reduced further by a bushing, which is welded to the shaft, and by putting grooves in the bearing seats.

The shaft overhang is affected considerably by the vibrational characteristics of the rotor bearing system. Satisfactory performance can be expected only if the rotor design speed is lower than the first critical shaft bearing system speed. As mentioned previously, computer programs have been employed with the heat transfer studies to determine the critical speed of the rotor bearing system. The computer program takes into account the temperature distribution along the shaft. Table VIII summarizes the results for various shaft configurations. All calculations are made for the highest test section temperature (1600°F). It is established that the geometrical relationship between overhang and the distance between the shaft bearings influences the magnitude of the critical speed. In the first set of calculations, an attempt was made to optimize the spacing between the bearings.

As shown in Table VIII and Figure 11, the critical speed can be increased if the bearing spacing is increased and the overhang remains constant. Because of limitations in over-all test rig length, complete advantage could not be taken of optimum bearing spacing. An 8-inch span was selected as a tolerable bearing spacing and conditions 4 and 5 in Table VIII were used to select a shaft overhang

TABLE VIII: CRITICAL SPEEDS FOR VARIOUS SHAFT CONFIGURATIONS

	Shaft Configuration	Bearing Stiffness, lb/inch	First Critical Speed, rpm
1.		1×10^6	7015
2.		1×10^6	7600
3.		1×10^6	8400
4.	 Shaft is tapered and has holes.	1×10^6	7360
5.	 Shaft is tapered and has holes.	1×10^6	5980

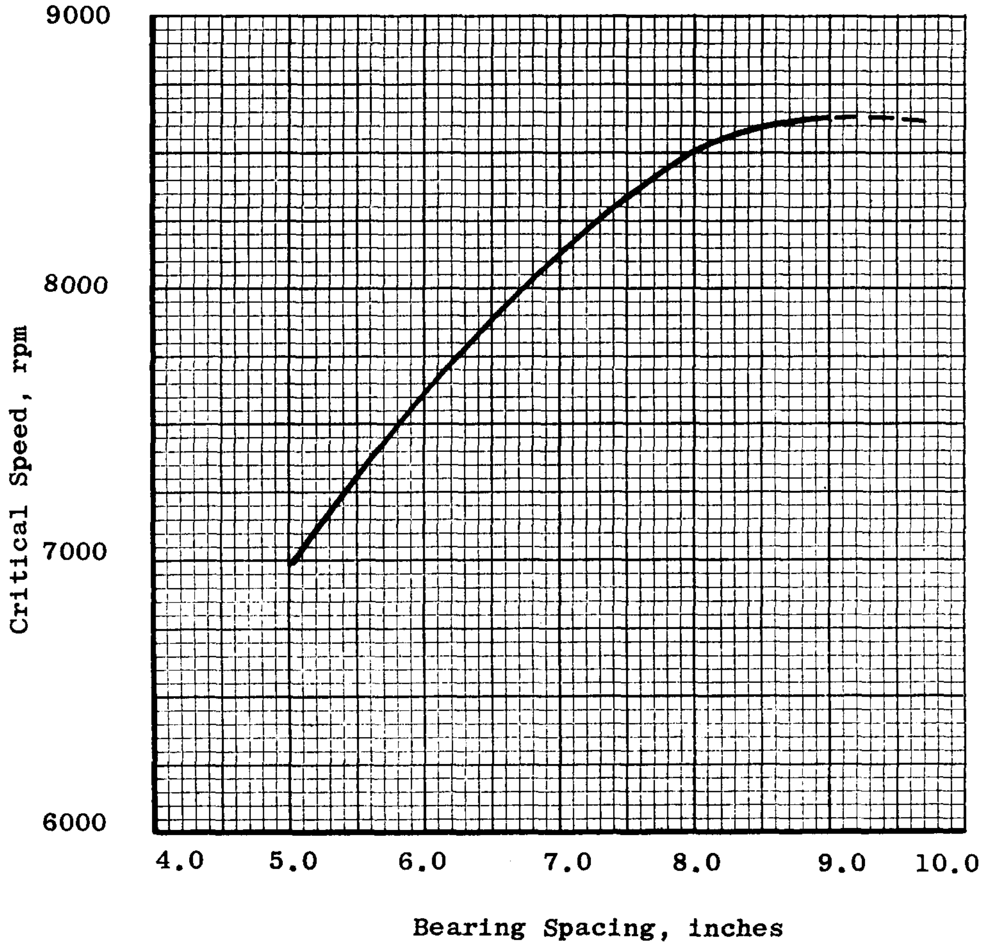


Figure 11. Effect of Bearing Spacing on Critical Speed

of 11.65 inches. Although this dimension differs slightly from that listed for conditions 4 or 5 in Table VIII, the first critical speed of the final spindle configuration was calculated at 6600 rpm by adjusting for the length. This speed is approximately 13.8% higher than the design speed and should be adequate.

Special gold plated M-50 angular contact ball bearings with silver plated, Circle C, fully machined retainers support the spindle, which carries the spindle overhang, the two wheels with the four disc-type test specimens at the lower end and the Alnico V magnet of the synchronous permanent magnet clutch on the top. The bearings have been installed in a water or liquid nitrogen cooled housing, so that the heat generated in the bearing while running is easily conducted into this heat sink. The bearings, preloaded by springs, can be removed easily and exchanged. Because of the particular arrangement of the four stationary rider specimens, bearing loading from the rider specimens is small. The largest load which the ball bearings must endure is the axial pull exerted by the magnetic clutch. The magnitude of this load is unknown now and can be determined only after the test rig has been assembled.

Magnetic Clutch and Drive-Motor. Operating a rotating spindle in a clean vacuum of approximately 10^{-9} torr is feasible only with hermetically sealed drive systems. Basically, there are two practical ways to transmit force through a continuous boundary. The most conventional method uses magnetic forces. This principle is applied in canned induction motors and in permanent and electromagnetic clutches and couplings. The second method transmits mechanical force through a deformable membrane. Since reliable systems of the latter type are not yet available, a synchronous permanent magnetic clutch has been selected.

Based on the experience with a very similar permanent magnetic clutch at NASA-Lewis Research Center for a comparable purpose[139] and the recommendations made by the Magnetic Materials Section, Metallurgical Products Department, General Electric Company, such a clutch of proper size should transmit as much as 5 hp at design speed. The clutch itself consists of two axially opposing, twenty-tooth permanent magnets separated by a cup shaped, 0.030-inch thick Inconel membrane. The clutch material is Alnico V. To avoid the possibility of clutch discs bursting at high speed, Inconel rings have been shrunk over the outer diameter of the magnets.

The distance between the two pole faces certainly affects the transmission efficiency of the clutch. To minimize the gap between the pole faces and the membrane, contour grinding of the pole faces is required. The transmission losses of a permanent magnetic clutch of this type occur in the diaphragm in the form of heat. Figures 12 and 13 show typical characteristics of a three horsepower coupling. Figure 12, furnished by the NASA-Lewis Research Center, is self-explanatory. Figure 13, furnished by the Magnetic Material Section,

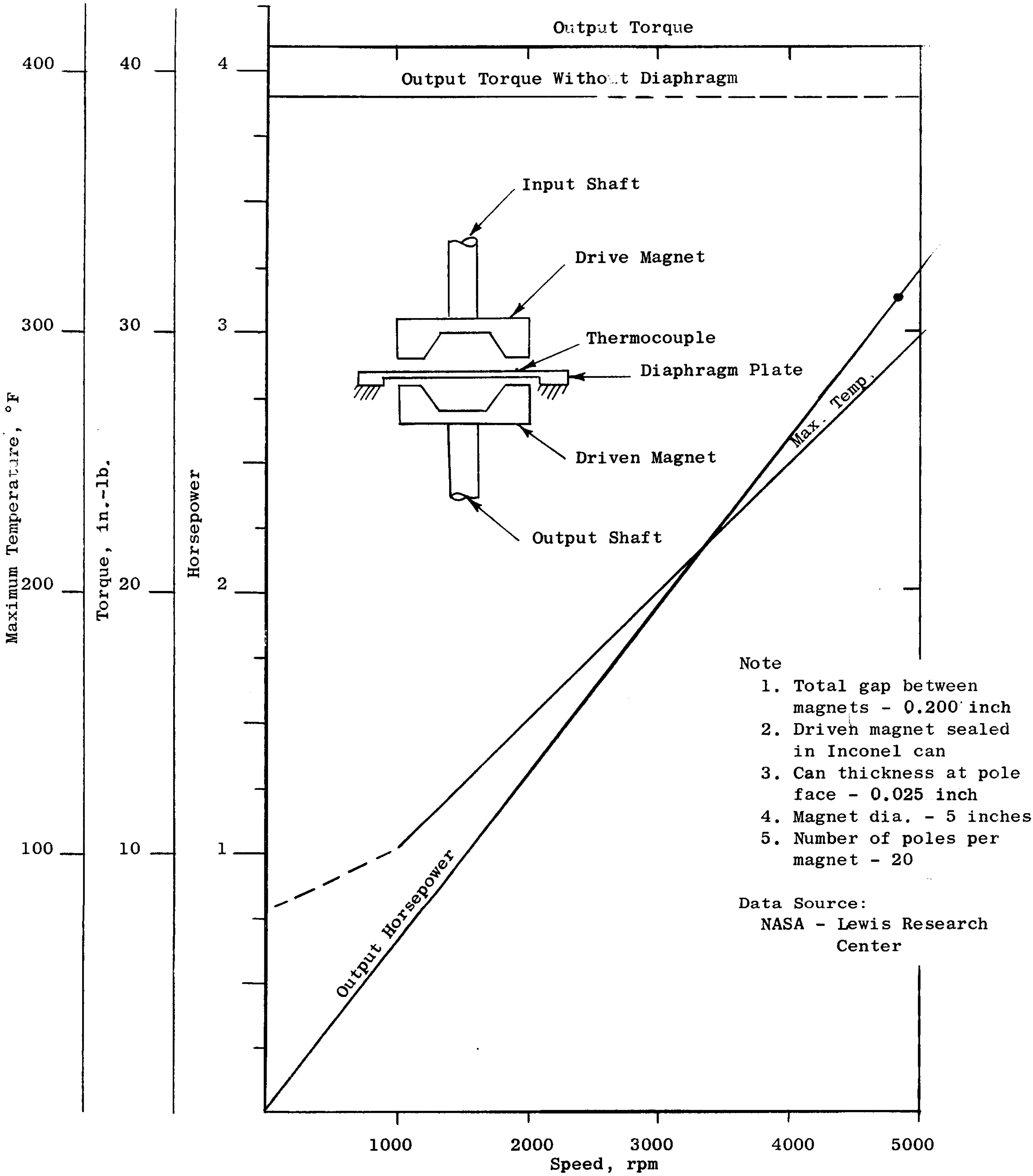


Figure 12. Operating Characteristics of a Three HP Magnetic Coupling

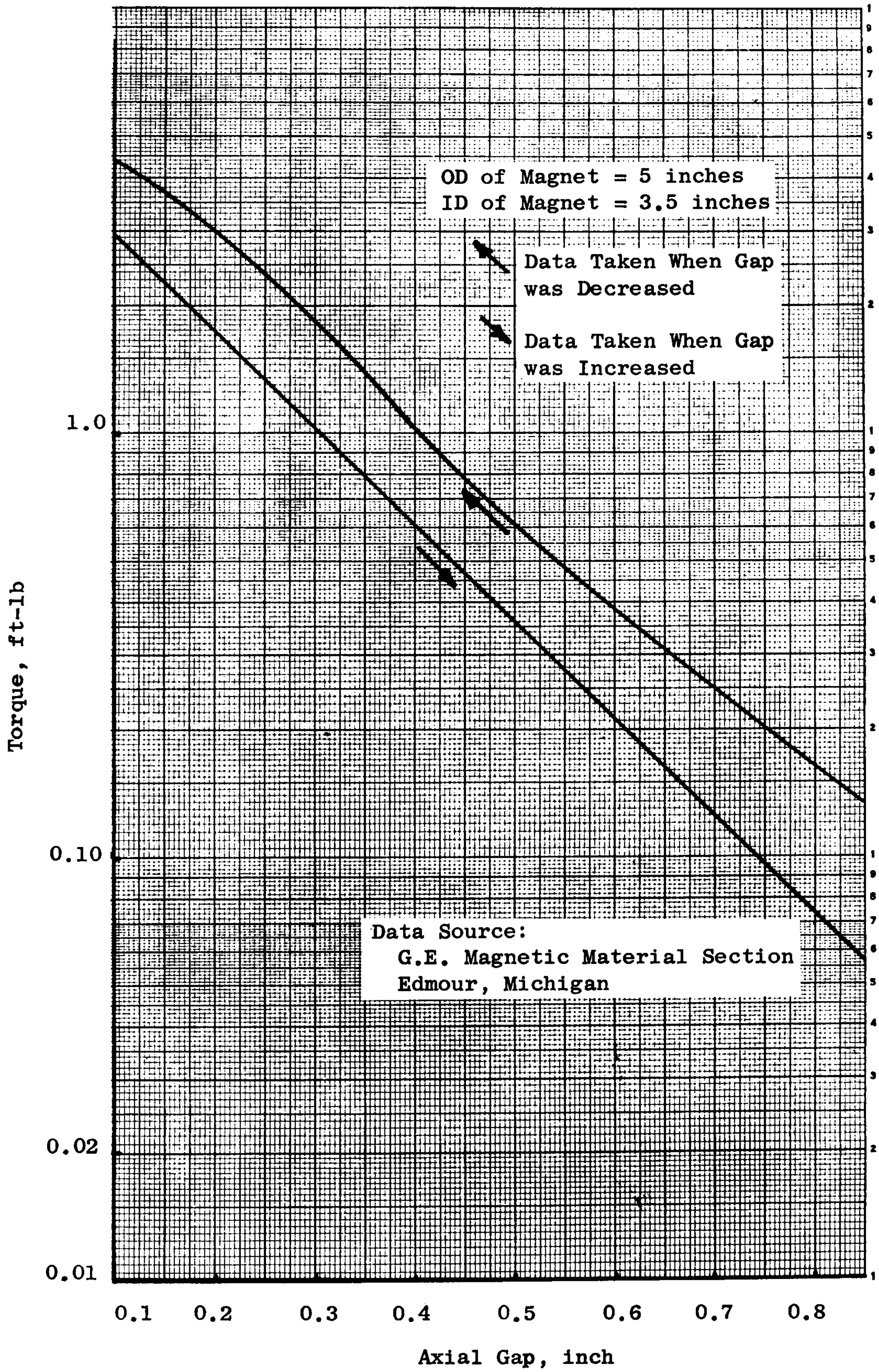


Figure 13. Performance of a Permanent Magnetic Clutch as a Function of the Axial Gap Between the Pole Faces

General Electric Company, shows the typical torque performance of such a clutch as a function of the axial gap between the two pole faces. For the bearing material test rig, the torque transmission capability of the magnetic clutch has been increased by enlarging the magnets' OD from 5 inches to 5.5 inches and decreasing the ID from 3.5 inches to 2.875 inches.

The outside magnet of the couple is attached to the shaft of the ball bearing mounted spindle which is mounted on top of the evacuated test rig housing. By three set-screws which are mounted in the flange of the spindle, the gap between the outside magnet and the membrane can be adjusted. The inside gap must be adjusted by shims. A special thymotrol motor drives the spindle by belt. The size and weight of the thymotrol motor and the aim to minimize vibrations introduced to the test rig from external sources like the motor led to the selection of the belt-driven spindle. The special thrymotrol motor has a 2% speed regulation at top speed, permits the speed to be preset over a 100 to 2500 rpm range and has a current-limit acceleration to avoid pull-out of the synchronous permanent magnetic clutch. The proper pulley wheel diameter ratio provides speed increase from 2500 rpm to the maximum design speed.

Instrumentation. During the design, considerable effort was made to place the necessary instrumentation and the associated read-out equipment outside the vacuum chamber whenever possible. The friction and wear test rig requires instrumentation for these measurements:

1) Test specimen loading

2) Torque caused by friction between candidate bearing materials

3) Temperature of the test section and the ball bearings

4) Spindle speed

5) Vacuum in the test chamber.

The four stationary test specimens, riding on the rotating test specimens, are individually mounted in four Rene' 41 loading arms which penetrate the side of the vacuum chamber wall and are connected to four stainless steel rods with sleeves and screws. These arms extend outward radially, 90° apart, into the atmosphere. Sealing between the atmosphere and vacuum is accomplished by flexible stainless steel bellows which are welded to the Type 304 SS rods and to the Type 304 SS conflat flanges that are attached to the outside of the vacuum chamber. The flanges are mounted on a sleeve which prevents excessive heat flow by radiation from the test section into the flange seats. The sleeve is undercut and is welded to the outside vacuum chamber section that surrounds the test section.

The load is applied at the end of the stainless steel rods by dead weights. Therefore, the only calibration required will be to tare-out the frictional loading on the arm caused by friction in the gimbal bearings of the load arm pivot and the resistance against deflection of the metallic bellows. Using the balance scale principle, with the gimbal bearing as the pivot, the calibration will be made on the completely assembled loading arm. Figure 14 is a schematic of the calibration apparatus. As planned, the load will be calibrated before each test with the stylus to be tested in position. This ensures that the stylus weight is factored into the calibration.

Four individual load cells, which determine the frictional pull of the loading arms, measure the frictional forces. The load cell is a ring type with four strain gauges mounted internally to form a bridge. Since the load on the strain gauge ring is always of a tensile nature, the bridge consists of two compensating and two recording gauges. Wiancko Force Pickups Type F1021 have been selected. Calibration of the force pickups, similar to the procedure used for calibrating the applied load, is as follows: The entire load arm assembly is mounted in the calibration fixture shown in Figure 14 and the correct weights for the planned test are placed on the load pan; a known load is applied to the side of the load that is being applied directly at the center line of the stylus; by varying this side pressure, a curve can be constructed showing side thrust versus load ring deflection. This calibration method assures high accuracy since the entire loading system is calibrated as a unit. The calibration of the force pickups will be made before each test.

The design of the friction tester calls for six permanent thermocouples in the test section area and two thermocouples for the test ring spindle ball bearings. The thermocouples for the test section are brought into the vacuum chamber through grooves provided in the loading arms. The thermocouple wires are brazed into these grooves and to the flexible metal bellow sleeve to form a vacuum seal. Their locations in the test section are as follows:

1) One thermocouple within each of the four loading arms terminating approximately 1/16 inch from the stylus specimen inside the arms.

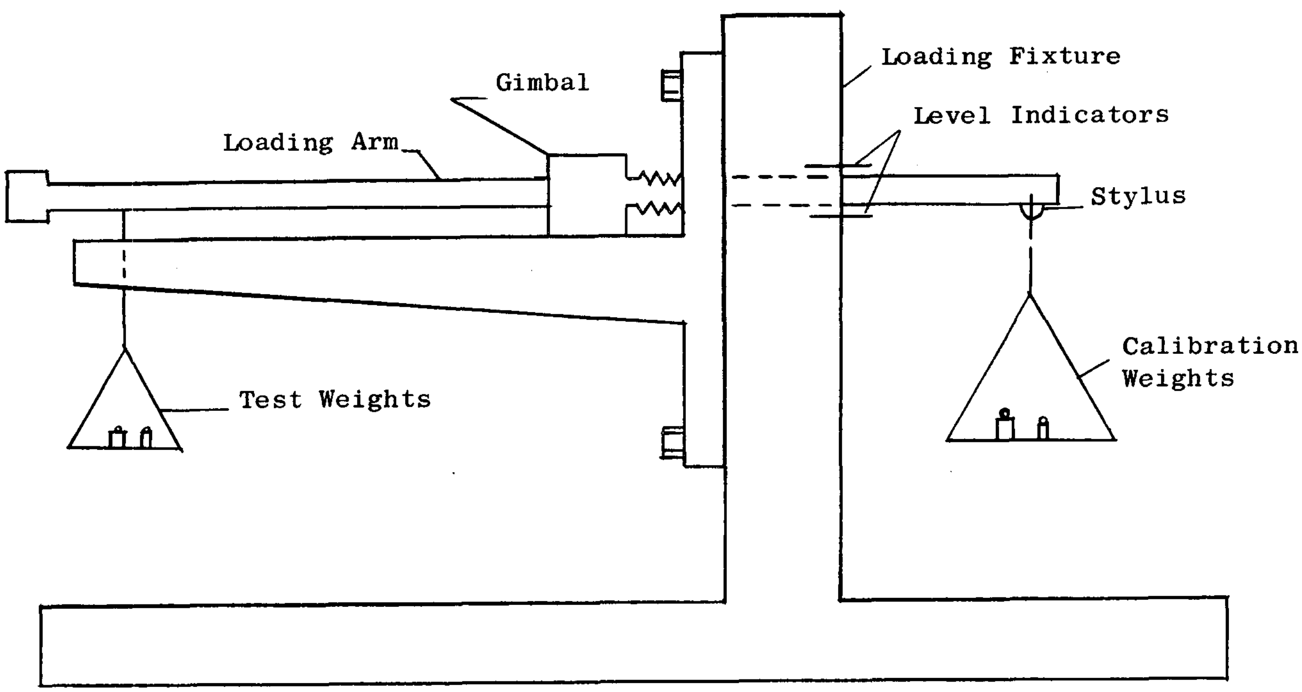


Figure 14. Test Setup for Calibration of the Loading Arm

2) One thermocouple outside each of two of the loading arms with the terminal point of the thermocouple extending into the heating plenum. (See Figure 15.) These thermocouples will measure the ambient temperature of the heat zone. One of the thermocouples will be used to record the temperature and the second thermocouple will be used as the control thermocouple for the saturable reactor temperature controller.

These six thermocouples should provide the necessary temperature profile to assure the accuracy of the test data.

In addition to the permanent temperature instrumentation, it is planned to have a spare loading arm equipped to measure the temperature of the stylus specimen. Figure 15 indicates schematically the manner in which this is accomplished. In this loading arm, a third groove is provided for the thermocouple that is to be located within the stationary stylus specimen through a hole either eloxed or abrasive drilled into the stylus. This allows a temperature measurement as close to the contact zone as feasible and indicates the differences between the arm and plenum temperatures and the actual temperature of the stationary test specimen (although away from the actual interface).

All thermocouples are swaged Pt vs. Pt + 10% Rh, Al_2O_3 (99.7%) insulated and Inconel or tantalum sheathed. This will provide the required temperature capability and assurance against contamination of the two thermocouples extending into the heating plenum. The thermocouples will be calibrated periodically according to accepted laboratory practice.

To obtain indications of the spindle bearing temperatures, one chromel-alumel thermocouple per bearing is imbedded in the housing wall as close as possible to the outer race of the bearings. All temperatures will be recorded during the tests on a Mineapolis-Honeywell multichannel strip-chart recorder. These recorders are on a monthly calibration schedule and recording accuracy is within 5% of indicated temperature.

Test spindle speed is indicated by the voltage output of an electromagnetic pickup, Model 3045, made by Electro Products Laboratories. The pickup is installed in the wall of the vacuum chamber between the bearings. A twenty-tooth gear attached to the spindle generates the frequency when the spindle is rotating. The electromagnetic pickup does not penetrate into the vacuum chamber but rather receives its signal through a thin walled section (0.060-inch) of the vacuum chamber. To receive sufficiently strong signals

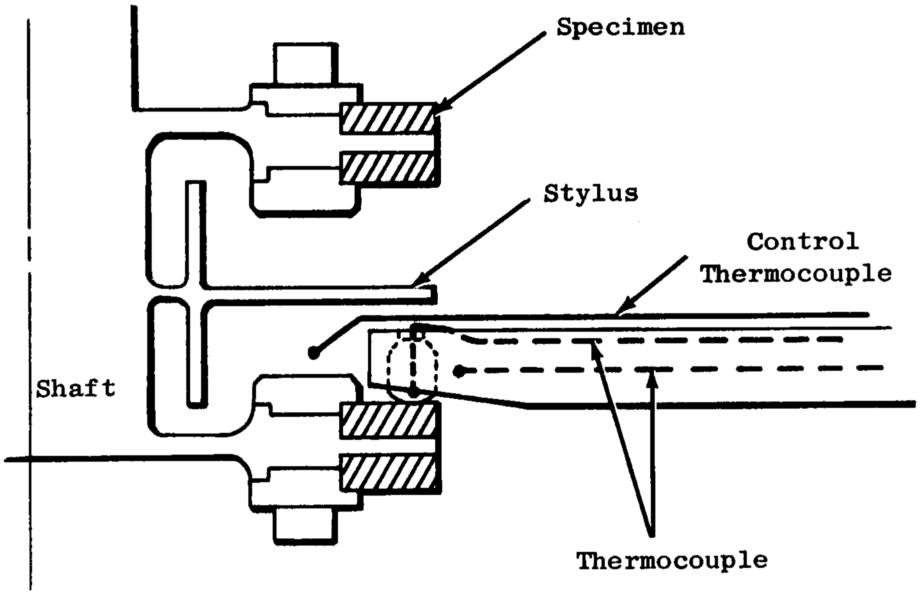


Figure 15. Location of Thermocouples in Vacuum Friction and Wear Test Apparatus

through the nonmagnetic Type 304 SS wall, a pickup with an extra high voltage output was selected.

The vacuum pressure is measured by a General Electric ionization gauge, Model 22GT102, with a General Electric ionization gauge control, Model 22GC100.

Liquid Potassium Friction and Wear Test Rig

Studies were initiated to determine the most satisfactory method of introducing the potassium into the friction tester, maintaining the proper flow over the test specimens and removing the potassium from the tester after completing the test run. From current indications, a pumped, recirculating system apparently offers the most satisfactory design. When more of the work has been completed, details of the design will be reported.

VII. FUTURE PLANS

The summary procedure which follows enumerates the steps to be pursued during the succeeding quarter to implement this research study.

1) Continued literature search and compilation of property data on candidate bearing materials.

2) Receive seamless tubing, sheet and wire of Cb-1Zr alloy for capsule corrosion test program.

3) Submit preliminary test plans to NASA for review and approval. These include tests for corrosion, hot hardness, compression, thermal expansion, dimensional stability, vacuum friction and wear and procedures for purification and analysis of potassium.

4) Initiate preparation of procurement specifications for candidate bearing materials.

5) Continue studies of the conceptual design of the liquid potassium version of friction and wear test apparatus.

6) Complete the detail drawings for the high vacuum friction and wear test apparatus.

7) Complete detail drawings for the isothermal corrosion capsule test facility and initiate drawings for the dimensional stability test facility.

8) Place order for vacuum chamber for compression tests.

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505 King Avenue
Columbus, Ohio 43200
Attn: C. M. Allen

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Cleveland, Ohio 44108
Attn: Mr. N. C. Beerli
Project Administrator

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P. O. Box 608
San Diego, California 92112
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Atomic Power Equipment Div.
P. O. Box 1131
San Jose, California

General Electric Company
Missile and Space Vehicle Dept.
3198 Chestnut Street
Philadelphia, Pennsylvania 19104
Attn: Librarian

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Vallecitos
Vallecitos Atomic Lab.
Pleasanton, California 94566
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P. O. Box 748
Fort Worth, Texas 76100
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Lockheed Aircraft Corporation
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Attn: Librarian

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Nuclear Division
P. O. Box 5042
Baltimore, Maryland 21220
Attn: Librarian

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Metals Technology Laboratory
Wheeling, Illinois

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Cambridge, Massachusetts 02139
Attn: Librarian

Materials Research and Development
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Cambridge, Massachusetts 02139

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Orangeburg, New York
Attn: Librarian

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St. Louis, Missouri 63100
Attn: Librarian

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Attn: Librarian

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Los Angeles Division
Los Angeles, California 90009
Attn: Librarian

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Attn: Librarian

Pratt & Whitney Aircraft
400 Main Street
East Hartford, Connecticut 06108
Attn: Librarian

Pratt & Whitney Aircraft
CANEL
P. O. Box 611
Middletown, Connecticut 06458
Attn: Librarian

Pratt & Whitney Aircraft Corporation
Division of United Aircraft
CANEL
P. O. Box 611
Middletown, Connecticut 06458
Attn: Glen Wood

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Farmingdale, Long Island, New York
Attn: Librarian

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Canoga Park, California 91303
Attn: Librarian

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West Nyack, New York
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Philadelphia, Pennsylvania 19100
Attn: Librarian

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2200 Pacific Highway
San Diego, California 92112
Attn: Librarian

Southwest Research Institute
8500 Culebra Road
San Antonio, Texas 78206
Attn: Librarian

Superior Tube Company
Norristown, Pennsylvania
Attn: Mr. A Bound

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Chem. & Metallurgical
Towanda, Pennsylvania
Attn: Librarian

Temescal Metallurgical
Berkeley, California 94700
Attn: Librarian

Thompson Ramo Wooldridge, Inc.
Caldwell Res Center
23555 Euclid Avenue
Cleveland, Ohio 44117
Attn: Librarian

Thompson Ramo Wooldridge, Inc.
Caldwell Res Center
23555 Euclid Avenue
Cleveland, Ohio 44117
Attn: G. J. Guarnieri

Thompson Ramo Wooldridge, Inc.
New Devices Laboratories
7209 Platt Avenue
Cleveland, Ohio 44104
Attn: Librarian

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Canton, Ohio 44706
Attn: Librarian

Union Carbide Metals
Niagara Falls, New York 14300
Attn: Librarian

Union Carbide Stellite Corporation
Kokomo, Indiana
Attn: Librarian

Union Carbide Nuclear Company
P. O. Box X
Oak Ridge, Tennessee 37831
Attn: X-10 Laboratory
Records Department

United Nuclear Corporation
5 New Street
White Plains, New York 10600-5
Attn: Librarian

United Nuclear Corporation
5 New Street
White Plains, New York 10600-5
Attn: Mr. Albert Weinstein
Senior Engineer

Universal Cyclops Steel Corp.
Refractomet Division
Bridgeville, Pennsylvania
Attn: C. P. Mueller

University of Michigan
Department of Chemical and Metallurgical Engineering
Ann Arbor, Michigan 48103
Attn: Librarian

Vanadium Alloys Steel Company
Labrobe, Pennsylvania
Attn: Librarian

Vought Astronautics
P. O. Box 5907
Dallas, Texas 75222
Attn: Librarian

Wah Chang Corporation
Albany, Oregon
Attn: Librarian

Westinghouse Electric Corporation
Astronuclear Laboratory
P. O. Box 10864
Pittsburgh, Pennsylvania 15236
Attn: Librarian

Westinghouse Electric Corp.
Materials Mfg. Division
RD#2 Box 25
Blairsville, Pennsylvania
Attn: Librarian

Westinghouse Electric Corp.
Materials Mfg. Division
RD#2 Box 25
Blairsville, Pennsylvania
Attn: F. L. Orrell

Wolverine Tube Division
Calumet & Hecla, Inc.
17200 Southfield Road
Allen Park, Michigan
Attn: Mr. Eugene F. Hill

Zirconium Corporation of America
Solon, Ohio
Attn: Librarian

Wyman-Gordon Company
North Grafton, Massachusetts
Attn: Librarian